AFFTC-TIM-05-10

# Demonstration of a Control Algorithm for Autonomous Aerial Refueling (AAR)

# (PROJECT "NO GYRO")

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FINAL TECHNICAL INFORMATION MEMORANDUM




AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIAL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum (AFFTC-TIM-05-10, Demonstration of a Control Algorithm for Autonomous Aerial Refueling (AAR), Project "NO GYRO") was prepared and submitted under Job Order Number M05C1000 by the NO GYRO test team, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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**14. ABSTRACT**
The report presents the results of tests to demonstrate a control algorithm for autonomous aerial refueling. The formation flight control system consisted of an attitude system, a positioning system, a data link, and a controller. Attitude information on the lead aircraft (C-12C) was measured with a Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU). Position information was provided with a student-designed differential GPS system (including an antenna, receiver, and small computer for processing on both aircraft), which passed information by datalink through antennas installed on both aircraft. Laptops on both aircraft displayed selected parameters and system information, and a pilot display on the Learjet provided current and commanded position information. The trail aircraft (Calspan LJ-25 Learjet) had a student designed control algorithm installed in the Variable Stability System (VSS) that scheduled the flight control surfaces and the throttles during close formation flight (fully autonomous control), while both aircraft simulated normal aerial refueling operations.

**15. SUBJECT TERMS**
No Gyro C-12 Aircraft LJ-25 Aircraft Autonomous Aerial Refueling Automatic Air Refueling DGPS (Differential GPS) IMU (Inertial Measurement Unit) Autopilot MEMS (Micro Electrical Mechanical System) Learjet Unmanned Aerial Vehicle (UAV) Joint Unmanned Combat Air Systems (JUCAS) Flight Testing Automated Formation Flight Test Controller

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Figure 1.  NO GYRO Test Aircraft

# PREFACE

The No Gyro test team would like to extend a special note of thanks to a few individuals whose efforts far exceeded our expectations, and without whom this project would not have been possible. Most notably, the work of Russ Easter and Brenna Stachewicz went well above and beyond requirements. Their technical competence and personal demeanor raise the standard of excellence we've come to expect from Calspan. We are very grateful for the late hours, and the innovative ideas that made system integration possible.

All of the support agencies involved in this project delivered outstanding service, but two other individuals at the Air Force Institute of Technology (AFIT) stood out in efforts in that literally saved the project. We are indebted to Mr. Don Smith, not only for the on-site engineering GPS support, but especially for the after-hours and weekend work to fix and turn hardware during the test. Finally, the No Gyro team wishes to recognize Dr John Raquet, who has been with the program from its genesis and who was a constant source of technical advice on all aspects of the attitude and GPS equipment. He was the original concept author, as well as the primary idea source for the heading estimator that was created during testing. Many thanks are due for the late phone calls, technical advice, and leadership.

Figure 2. System Ground Testing on the C-12

# EXECUTIVE SUMMARY

The No Gyro Test Team from the USAF Test Pilot School (TPS) at Edwards AFB, CA performed flight tests to demonstrate autonomous aerial refueling with a USAF C-12 and a Calspan Learjet LJ-25. An autonomous formation flight control system was provided by the Air Force Institute of Technology (AFIT) as the culmination of two students' theses. The flight control algorithm autonomously flew the Learjet (trail aircraft) during simulated air refueling. The test team demonstrated the operation of the system as a whole, and specifically demonstrated the ability of the system to move between and maintain three formation positions (contact, pre-contact, and wing observation). The test team also recorded all system inputs and outputs from the flight controller for post flight analysis.

This report presents the test results of the No Gyro Test Management Project (TMP). The No Gyro TMP was conducted at the request of the Air Force Institute of Technology, Department of Systems Engineering (AFIT/SYE). The Commandant of USAF TPS directed this program at the request of AFIT/SYE. All testing was accomplished under TPS Job Order Number M05C1000. A total of 12.6 hours on the Learjet and 13.1 hours on the C-12 were flown. Flights were conducted in the R-2508 complex during October 2005 to accomplish the test objectives.

The formation flight control system consisted of an attitude system, a positioning system, a data link, and a controller. Attitude information on the lead aircraft (C-12C) was initially measured with a Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU). Heading and pitch angle were replaced by data from estimators during testing due to an IMU malfunction. Position information was provided by a student-designed differential GPS system (including an antenna, receiver, and small computer for processing on both aircraft). The system passed information by datalink through an antenna installed on both aircraft. The trail aircraft (Learjet) had a student designed control algorithm installed in the Variable Stability System (VSS) that scheduled the flight control surfaces and the throttles. Laptops on both aircraft displayed selected parameters and system information, and a pilot display on the Learjet provided current and commanded position information.

The controller maintained each of the three required positions (contact, pre-contact, and wing observation) during straight and level flight and during established turns of 15 or 30 degrees of bank well enough to safely refuel off of a KC-135 or KC-10 tanker. During rolls into and out of bank, however, the controller sometimes displayed lateral errors that exceeded tanker boom limits. Safety of flight was never in question. The controller was also successful with all position changes, including changes performed while turning, and when turns were initiated while the trail aircraft was between positions.

The results from the No Gyro Project and lessons learned (listed in appendix E) may be applied with the lessons in controller design techniques (reference 1) to the design of the Joint Unmanned Combat Aerial System (J-UCAS) automated refueling program.

Figure 3.  Approaching the Contact Position

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**Figure 4. NO GYRO Test Team**

# INTRODUCTION

## *Background*

The capability to refuel autonomously was being developed for use on the Joint Unmanned Combat Air System (J-UCAS). Automated air refueling was a force multiplier to greatly increase range, flexibility, global responsiveness, and station time. The No Gyro Test Team effort was a proof of concept for autonomous aerial refueling. A control system was designed as a Master's thesis by a student in the joint Air Force Institute of Technology (AFIT)/Test Pilot School program. This controller scheduled control surfaces and power settings based on position information from a differential GPS designed as another student project, along with attitude information from a simulated tanker. A USAF C-12C simulated the tanker, and a Calspan Learjet LJ-25 simulated an unmanned receiver. The control algorithm simulated picking up control after a rejoin, and autonomously controlled the Learjet through simulated refueling operations. Specifically, the aircraft maneuvered between the contact, pre-contact, and wing observation positions, and held each position within certain tolerances during straight and turning flight. The Lost Wingman Test Management Project (TMP, reference 2) tested the datalink and GPS hardware in April 2005 as a risk reduction for this test.

## *Program Chronology*

Aircraft modifications were completed on 03 October 2005. Flight testing was conducted between 4 October and 14 October 2005, as shown in Table 1.

**Table 1. Program Chronology**

| Date | Testing Accomplished |
|---|---|
| 29-Aug-05 | Ground checkout of C-12 differential position solution |
| 3-Oct-05 | Ground checkout of C-12/Learjet interoperability |
| 5-Oct-05 | Initial system calibration flight: (auto-throttles inoperative, Inertial Measurement Unit unreliable, large swings in heading and pitch) |
| 6-Oct-05 | Second calibration flight: (IMU heavily filtered or inputs replaced with constants, auto-throttles inoperative) |
| 11-Oct-05 | System test flight #1: auto-throttles used, IMU heading and pitch angle replaced with estimators; turning capability introduced, but incorrect due to transformation error |
| 12-Oct-05 | System test flight #2: Heading estimator modified, filters modified, turning introduced |
| 12-Oct-05 | System test flight #3: Filters modified – System fully Capable |
| 13-Oct-05 | System test flight #4: Stable configuration - System performance data collected |
| 14-Oct-05 | System test flight #5: Stable configuration - Completed data collection |

## *Test Item Description*

The system under test (SUT) consisted of equipment on both aircraft. On the lead aircraft (C-12C), the system included a datalink antenna, datalink transceiver, GPS receiver, Micro-Electro-Mechanical System Inertial Measurement Unit (MEMS IMU), and a PC-104 computer with differential GPS software and a laptop display. Modifications are explained in detail in references 3 and 4. On the trail aircraft (Learjet), the system included a datalink antenna, datalink transceiver, GPS receiver, PC-104 computer with differential GPS software and a laptop display, software installed in the Variable Stability System (VSS) of the Learjet, and a pilot display of current and commanded positions, mounted on the instrument panel.

Attitude information for the C-12 was initially determined by the IMU (later hardware failures required estimators to be designed for heading and pitch angle). The GPS receiver in the C-12 was spliced into a GPS antenna mounted on the tail. The data received by the GPS antenna and the attitude information were then sent from the lead aircraft through the datalink to the trail aircraft, and into the Learjet's PC-104 computer. This component was manufactured by Diamond Systems Corporation, and had a Linux® operating system with specialized software for this application. The datalink transmitter transmitted at 1 Watt over the omni-directional datalink antenna at a frequency of 902 to 928 MHz. The GPS receiver in the Learjet was spliced into a GPS antenna installed on the top of the Learjet Fuselage. The measurements (pseudo-ranges and ephemeris codes) from the GPS receiver in the Learjet were sent into the PC-104 computer, where the differential position solution between the aircraft was calculated. The differential GPS algorithm was designed as an AFIT thesis project and flight tested as part of the Lost Wingman TMP (reference 2). The relative position solution and lead attitude information were displayed in both aircraft on a laptop, and were transmitted to the VSS MIL-STD-1553 data bus, where individual parameters were drawn into the controller.

The controller was also designed as an AFIT thesis project (reference 1), and was installed in the VSS computer. Essentially, the controller took the North-East-Down relative actual position vector from the lead aircraft and transformed it into the body axis coordinate frame of the lead aircraft. The desired position vector was also generated in the controller, and was based on where the GPS antennae on a KC-135 and a J-UCAS would be during refueling. The controller software generated the desired position vector based on inputs from the flight test engineer (FTE) in the Learjet (options included "hold current", contact, pre-contact, an intermediate "back corner" position, and wing observation positions). The FTE had the ability to change the command at any time during the flight. Based on the input, the controller automatically scheduled the correct sequence of maneuvers to move to the new commanded position, and then moved the desired position vector at a speed which was adjustable by the FTE in-flight. An error vector was produced from the difference of the desired position vector and the actual position vector, again in the tanker body frame. Proportional plus integral plus derivative control was applied to the components of the error vector and used to determine control commands (vertical error applied to the elevator, longitudinal to the throttles, and lateral to the ailerons). Rudder control was provided in the form of a yaw damper, but the rudder did not direct position control. The actual coordinates of the vector to the formation positions (contact, pre-contact and wing observation) was also adjustable in-flight, as were the control gains. Several filtering options were added during testing, which also were selectable.

Table 2 documents the manufacturer and model or part numbers of the system components.

**Table 2. System Components for the No Gyro TMP**

| **Component** | **Model** | **Manufacturer** |
|---|---|---|
| Datalink Transceiver | PCFW-104 OEM | Microbee Systems, Inc |
| DC Power Supply | HE104MAN-V8 | Tri-M Engineering |
| Embedded PC | ATH-400 Athena | Diamond Systems, Inc |
| GPS Receiver Card | JNS100 OEM | Javad Navigation Systems |
| MEMS IMU | MIDG II INS/GPS | Microbiotics, Inc |
| UHF Datalink Antenna | P/N 6008 | Haigh-Farr |

## *Test Team*

The test team consisted of five members (three pilots, two flight test engineers) of TPS Class 05A at the USAF Test Pilot School, a Calspan pilot, and a Calspan Engineer.

## *Test Objectives*

The overall objective was to demonstrate the performance of an automated air refueling control algorithm in an operationally representative environment. This overall objective was broken into three sub-objectives:

1. Observe selected parameters in the system under test.
2. Demonstrate that the SUT was capable of maintaining the pre-contact, contact, and wing observation positions.
3. Demonstrate that the SUT was capable of moving between the pre-contact, contact, and wing observation positions.

All objectives were met.

## *Limitations*

None.

Figure 5.  DGPS, VSS, and Crew Stations in the Learjet

# TEST AND EVALUATION

## *General*

The overall objective was to demonstrate the performance of an automated air refueling control algorithm in an operationally representative environment. This overall objective was broken into three sub-objectives: observe selected parameters in the system under test (SUT), demonstrate that the SUT was capable of maintaining the pre-contact, contact, and wing observation positions, and demonstrate that the SUT was capable of moving between the pre-contact, contact, and wing observation positions.

Approximately 6 hours of ground test to verify system functionality were conducted prior to flight test. Flight time consisted of 12.6 hours in the Learjet and 13.1 hours in the C-12 on two calibration sorties and five flight test sorties (all sorties were flown as a two-ship formation) in the R-2508 complex during October 2005 to accomplish the test objectives. The design flight condition was 10,000 feet and 190 KIAS. All flights were accomplished there except flight number 5, which was flown at 12,000 feet in an effort to reduce turbulence.

## *SUT Parameters*

The first test objective was to observe the parameters listed in appendix B.

### Procedures

GPS Aided INS (GAINR), Data Acquisition System (DAS), and SUT data were recorded for each maneuver. Tables B-1 and B-2 list the data parameters collected on each aircraft.

### Results

Data were recorded during each test matrix maneuver and during points of interest during the sortie. The amount of data collected exceeded customer requirements, and is provided in the supplemental data package.

## *Position Maintenance*

The second test objective was to demonstrate that the SUT was capable of maintaining the pre-contact, contact, and wing observation positions.

### Procedures

The SUT was commanded to fly the pre-contact, contact, and wing observation positions during straight and level flight and in 15 and 30 degree banked turns (including roll in and roll out, as in an operational refueling track). The capability of the system to remain in the desired positions was measured. The location of each of these positions, as well as criteria which define acceptable error envelopes are attached in appendix A. For each position and maneuver, several plots were produced: a plot of X, Y, and Z body axis errors, a plot of pitch angle, yaw angle, roll angle, and roll rate of the lead aircraft, and a plot of control surface position and commands versus time. Representative samples of these plots are attached in appendix C. Additionally, qualitative comments and ratings from pilots were gathered to provide information on the algorithm performance during refueling operations. The test team used these to characterize the system and to identify factors that may have caused degraded refueling performance.

## Results

In the contact position, the system demonstrated the ability to remain within acceptable error limits (defined in appendix A) during straight and level flight. At no point did the system exit a notional KC-135 boom envelope. The longest data run recorded in contact was for 10 minutes and the total position errors are shown in Figure 6. This run was representative of the straight and level performance seen in all positions for the controller.

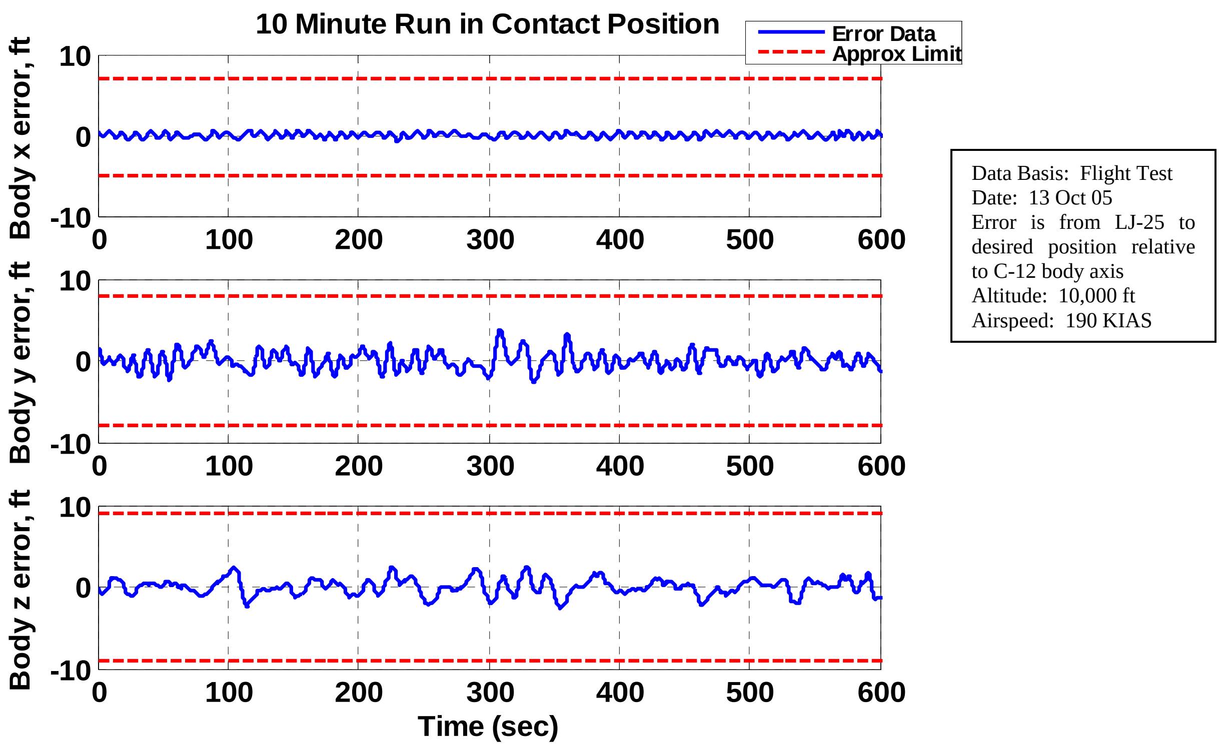



**Figure 6. Contact, Straight and Level Flight**

The mean radial error for this 10 minute run was 1.33 feet, and maximum radial error was 3.9 feet.

Two recurring sources of error were observed in all phases of flight. First, the heading and pitch angle information from the IMU was unusable due to a hardware malfunction. The heading angle of the lead aircraft swung rapidly from the correct heading to a value 30-40 degrees off, as shown in Figure 7. A similar error occurred in the pitch angle. An option that added magnetometer corrections to the data when reaching 8 degrees of heading uncertainty, was available for the IMU. Though this option was turned off, the data suggested there was a firmware error that was adding the “correction” anyway (and that the “correction” was adding the 30-40 degree error). This assumption was supported by the timing of the bias addition. In straight and level flight, GPS corrections were not added to heading. After 45 to 60 seconds, the uncertainty in the MEMS gyro most likely grew enough to trigger magnetometer "corrections". As the aircraft started to turn, the GPS corrections to heading were added, and usually (though not in every case), the heading and pitch angles would re-capture as shown in Figure 7. With random errors of such large magnitude, the heading and pitch angles were unsuitable for use. **Repair or replace the IMU before further flight test (R1)**[1]**.**

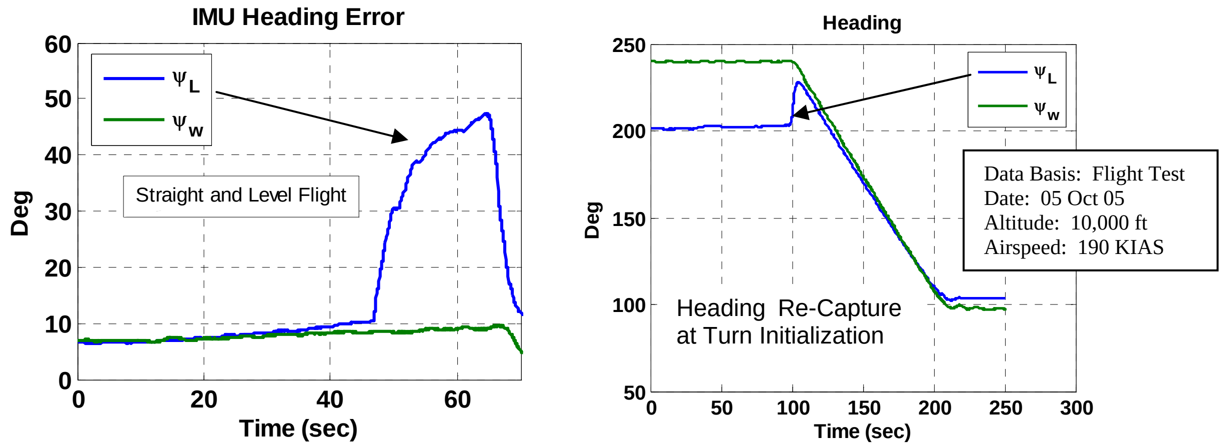



Figure 7. IMU Errors

For the second flight, constants were used for tanker attitude (heading was hard-coded in flight by the FTE and no turns were allowed). A heading estimator was installed by the third flight, which used the lead aircraft's bank angle and the wing aircraft's heading to form a blended solution. While this solution was adequate for flight test, some "wander" in the data existed. Figure 8 shows characteristic performance.

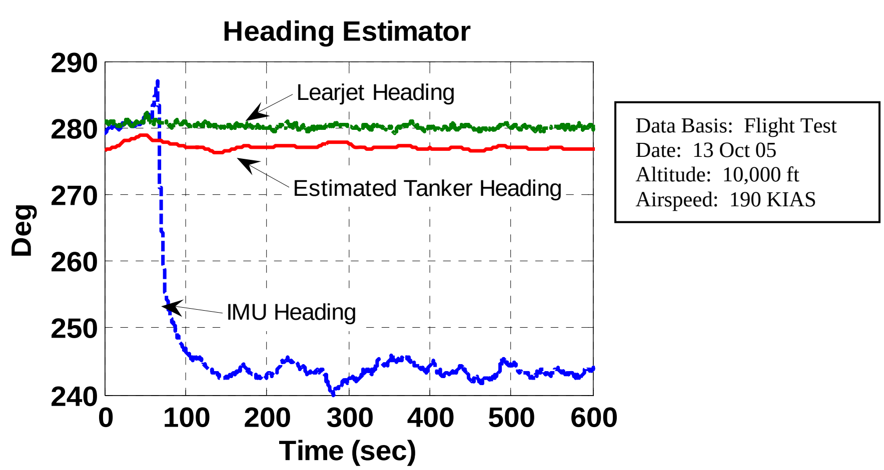



Figure 8. Heading Estimator During Ten Minute Straight and Level Run

[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

The Learjet crew noted that during periods of lead heading error, the trail aircraft settled into a position offset from the C-12 centerline, yet showed zero position error. When the heading of the lead aircraft wandered, the desired position behind the lead aircraft moved as well, giving the trail aircraft a moving target to maintain instead of a stable position. The amount of position error attributable to this effect was difficult to estimate when the aircraft was not straight and level (the times when the errors were most significant). It was not determined exactly how much position error was due to the controller, and how much was attributable to the lack of a heading source.

The second recurring error which affected performance was throttle asymmetry. The servo operating the fuel control unit on the right engine of the Learjet was receiving a low quality RPM signal. In effect, this caused a "sticky throttle" that did not move until a large signal was input. There was insufficient time in the test schedule to replace the part. For small errors, such as those generated when station-keeping and falling slightly aft, the left throttle would move forward to correct it, but the right would not. This asymmetry caused yaw which generated lateral error. As the aft displacement was corrected, the ailerons corrected the lateral displacement, but the left throttle would move back to arrest forward motion (and the right would not). The end result was a coupled oscillation. This effect was intermittent, and only pronounced (as shown in Figure 9) a few times during testing. Exactly how much lateral error in each maneuver was due to the asymmetric thrust was not determined.

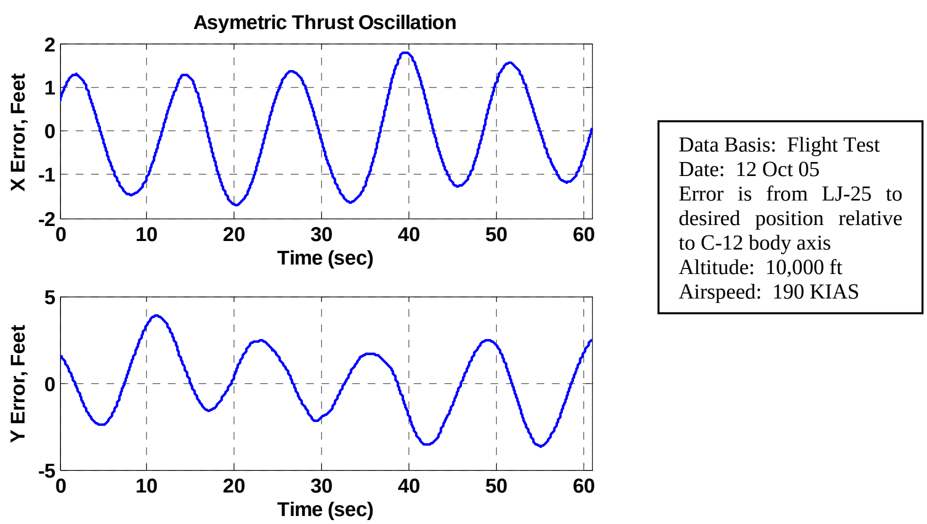



Figure 9. Effects of Asymmetric Thrust. Contact Position. Straight and Level Flight.

During turning flight to 15 degrees of bank (the planned bank angle for a tanker track), the performance of the controller was directly impacted by the roll rate and smoothness of the lead aircraft. Maneuvers with abrupt stops or abrupt roll initiation increased the lateral overshoot. Once the turn was established, the controller stayed within boom position limits with small enough deviations to easily refuel. During the rolling portion of the maneuver, however, the lateral error exceeded the limits on one of the 15 degree banked turns. Figure 10 shows an acceptable turn.

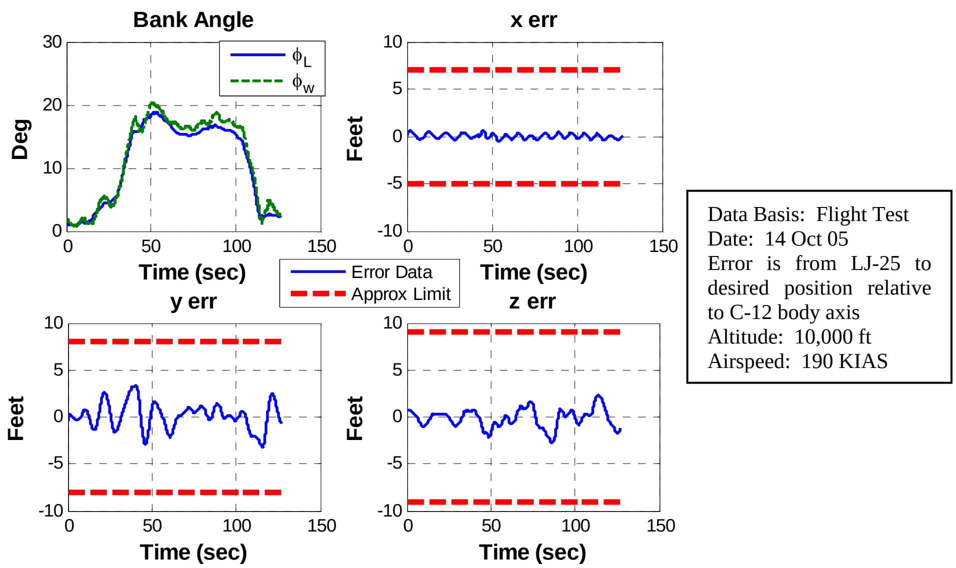



Figure 10. Contact Position, Smooth 15 Degree Right Turn, Acceptable Performance

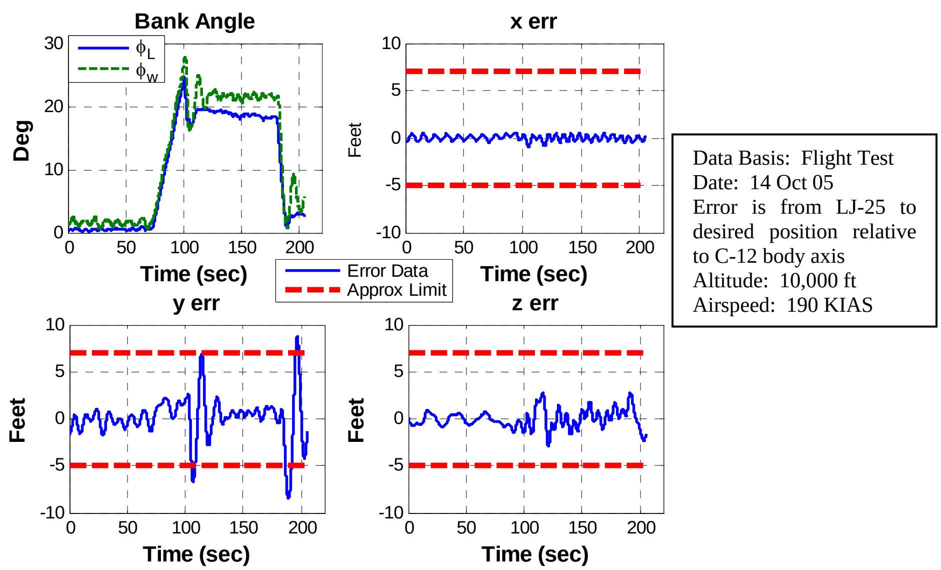
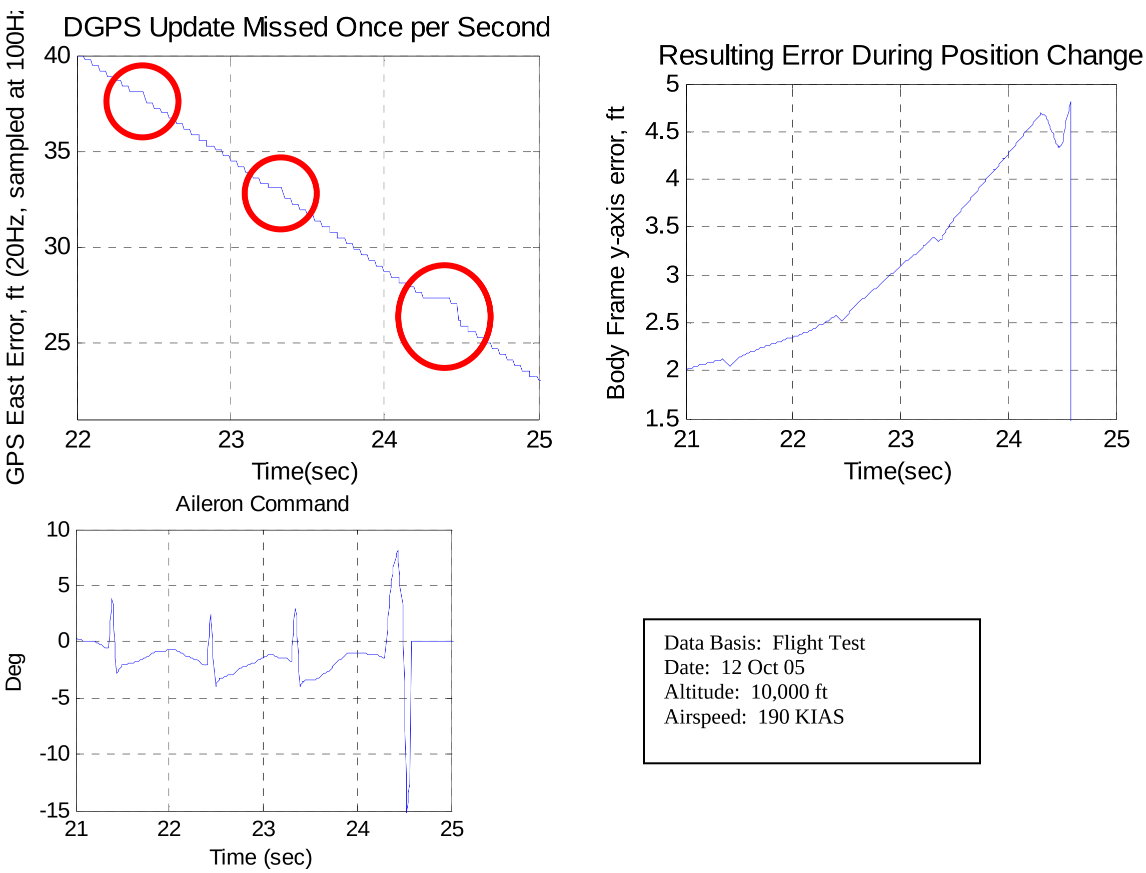



Figure 11. Nineteen Degree Banked Turn with Lead Aircraft Overshoot and Rapid Roll-Out. Unacceptable Performance.

Figure 11, however, shows a turn where the controller exceeded the notional boom limits (these limits are estimates, as the boom envelope is not square—slightly more allowable error exists in each channel if you are in the heart of the other two channels). The C-12 autopilot was malfunctioning, and the pilot was only able to attain an extremely slow roll in, which overshot and corrected back rapidly to a steady state value slightly higher than intended (approximately 19 degrees). The roll-out was performed with a different technique which had a faster roll rate and another slight bank overshoot. The controller was not able to acceptably maintain position laterally. Though this turn was not the smooth, slow roll expected of a tanker with a receiver on the boom, it is not unlikely that a J-UCAS would see similar conditions at some point, and it represents a good limit to what the controller can handle in the configuration tested.

The lateral channel was characterized by one sizable overshoot (magnitude varied based on the lead aircraft's maneuver). Some of this "error" was simply geometric change. As the tanker rolls to the left, the "desired position" actually moves to the right. An "error" shows on the plots, but this is acceptable—the receiver should not roll right to minimize that error in response to a left roll from the tanker. The second "hump", however, shows overshoot that the controller should have corrected, but was too slow in banking into the turn. A majority of this error can be contributed to reduced lateral gains.

Pre-flight analysis had shown possible difficulty with the derivative control magnifying sensor noise. The lateral gains were reduced to 30 percent of the design value before the first flight, and filters were installed to smooth the sensor data. The intention was to get the system flying, apply the lessons learned, and to adjust the gains back up when time for tuning was available later in testing. Time compression in the schedule and hardware failures, however, kept the team from that opportunity. Much of the suspected "noise problem" turned out to be a DGPS error. One position update per second was missed, resulting in a 1 Hz "kick" noted in the flight controls as shown in Figure 12.




| |
|---|
| Data Basis: Flight Test<br>Date: 12 Oct 05<br>Altitude: 10,000 ft<br>Airspeed: 190 KIAS |

Figure 12. Differential GPS Missing Updates Causing Aileron "Kicks"

When holding position, the effect of this missed update was small enough to go unnoticed—the magnitude was small, and only resulted in a “flat spot” in the position data that would be filtered anyway prior to going to the control laws (specifically to the derivative control). During position changes, however, the “kick” was obvious, annoying, and large enough to occasionally cause VSS safety disconnects in the aileron channel when moving laterally, and in the throttle channel when moving forward. This was a result of the controller structure. The GPS data (north, east, down relative position vector) was smoothed as it first entered the system. It was then subtracted with the “desired position vector” to yield a “position error vector” that would be corrected by the controller. The subtraction happened *after* the filtering. When the “desired position” was moving (during a position change), “corners” appeared in the error, shown in the upper right of Figure 12. These “corners” were a result of the desired position moving slightly while the relative position did not. The high frequency content was then fed directly to the controller, and the derivative control commanded the “kick”.

After flight 5, a “flat spot” detector and predictive filter were created and installed which guessed the next step in DGPS data at every missed epoch. The filter effectively smoothed out the DGPS data, but could only handle one missed epoch. The large errors caused by several missed epochs still passed through and would still cause large control motions and disconnects. The DGPS data smoothing filter was moved to after the vector subtraction, where it had more impact on the higher frequency “corners”. The filter structure change, and the addition of the predictive filter overcame the problem. Figure 13 shows plots for the same portion of the same maneuver (on the next flight) as Figure 12 after the software patches for the DGPS problem were installed.

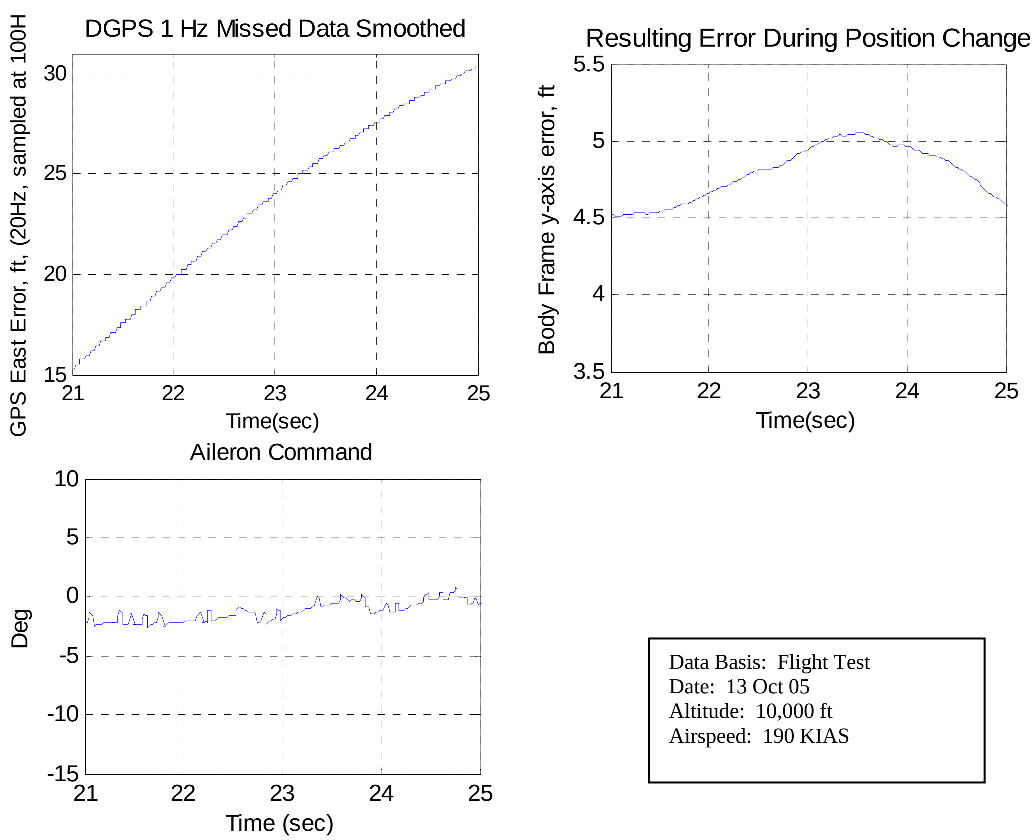



Figure 13. Control With 1 Hz DGPS Missing Updates Smoothed

By the time this problem was resolved, the test team did not have time to tune the aileron channel gains and restart the test matrix. The testing was continued with the reduced gains, and the performance directly suffered. This is seen in the large errors during 15 degree banked turns, and especially in the 30 degree banked turns shown in appendix C and summarized in Table 3. Thirty percent of design aileron use was not sufficient to get the turn going quickly enough or to stop the overshoot. **Reduce lateral error during rolling maneuvers (R2).** If time had permitted and the hardware had not failed, a much more accurate analysis of the controller's capability could have been accomplished. **Repeat rolling maneuver testing in the contact position with an operative heading system on the lead aircraft, a repaired throttle servo, and the design gains (R3).**

The design requirements for the pre-contact and the wing observation positions were not nearly as stringent (listed in appendix A). Essentially, the controller needed to maintain the position without becoming a hazard to other receivers in the formation. The tightest position error constraint was a +/- 10 foot lateral requirement in the wing observation position, which was relaxed to a 12 foot error to the outside of turns during roll ins (since all receivers will show "error" to the outside of a turn as the tanker begins to pull away). Table 3 summarizes the average and maximum absolute errors for each position in straight and level flight (SLUF) and in turns (including the dynamic portions both in and out). Representative plots for each of these maneuvers are attached in appendix C.

**Table 3. Summary of Position Errors**

| SLUF | Avg. Absolute Error (ft) | | | Max Absolute Error (ft) | | | Avg Radial Error (ft) | Max Radial Error (ft) |
|---|---|---|---|---|---|---|---|---|
| | x | y | z | x | y | z | | |
| Contact | 0.26 | 0.85 | 0.73 | 0.81 | 3.85 | 2.71 | 1.29 | 3.92 |
| Precontact | 0.27 | 0.97 | 1.07 | 0.65 | 2.69 | 2.57 | 1.54 | 3.34 |
| Wing Obs. | 0.24 | 1.08 | 0.90 | 0.74 | 3.15 | 2.30 | 1.57 | 3.34 |
| Established in 15° bank | | | | | | | | |
| Contact | 0.22 | 0.78 | 0.83 | 0.55 | 2.20 | 2.84 | 1.27 | 2.92 |
| Precontact | 0.26 | 1.23 | 0.79 | 1.02 | 4.44 | 2.30 | 1.65 | 4.47 |
| Wing Obs. | 0.17 | 0.68 | 0.71 | 1.13 | 2.30 | 2.85 | 1.15 | 2.92 |
| 15° turn with roll dynamics | | | | | | | | |
| Contact | 0.23 | 1.40 | 0.91 | 0.72 | 9.3 | 3.09 | 1.87 | 9.3 |
| Precontact | 0.29 | 2.64 | 0.83 | 1.02 | 10.39 | 2.67 | 2.95 | 10.41 |
| Wing Obs. | 0.45 | 1.66 | 1.00 | 4.18 | 11.60 | 6.36 | 2.25 | 11.62 |
| Established in 30° bank | | | | | | | | |
| Contact | 0.32 | 1.33 | 1.61 | 1.75 | 6.12 | 7.31 | 2.36 | 7.57 |
| Precontact | 0.33 | 2.25 | 1.52 | 0.92 | 5.83 | 4.16 | 2.94 | 7.07 |
| Wing Obs. | 0.28 | 0.87 | 1.43 | 2.49 | 3.58 | 6.38 | 1.86 | 6.70 |
| 30° turn with roll dynamics | | | | | | | | |
| Contact | 0.32 | 1.93 | 1.52 | 2.44 | 15.19 | 7.52 | 2.82 | 15.21 |
| Precontact | 0.34 | 3.21 | 1.52 | 1.17 | 13.39 | 4.16 | 3.85 | 13.47 |
| Wing Obs. | 0.45 | 1.84 | 1.55 | 3.13 | 11.14 | 7.20 | 2.82 | 11.35 |

In summary, the capability of this system to maintain formation position was good, but not sufficient for operational use. Station-keeping in straight and level flight was satisfactory with no changes. Performance when established in 15 degree turns was also satisfactory. Performance during rolling maneuvers, however, had the potential to cause a refueling disconnect in turns (depending on the roll rate and abruptness of the lead aircraft). Performance may be significantly improved with the gains reset to the design conditions (as well as with an operational heading source and with a repaired throttle servo, though these are smaller effects).

## *Position Changes*

The last test objective was to demonstrate that the SUT was capable of moving between the pre-contact, contact, and wing observation positions.

### Procedures

The SUT was commanded to transition between the pre-contact, contact, and wing observation positions during both straight and level flight (SLUF) and in both 15 and 30 degree banked turns (including turns initiated while the test aircraft was mid-transition). GPS differential position was measured and recorded to determine the SUT's capability to remain within the evaluation criteria listed in appendix A during transition. Additionally, qualitative comments and ratings from pilots were gathered to provide information on the algorithm performance during refueling operations. The test team used these comments to identify additional factors that may cause degraded refueling performance.

### Results

The SUT demonstrated satisfactory performance for all types of position changes, including those performed when established in turns and when turns were initiated while changing position. The limits for desired performance during a position change are listed in appendix A. The limits are operationally representative and as such are not tightly restrictive. Essentially, the aircraft was required to follow the correct path and never encroach upon airspace that may be occupied by the tanker or another receiver. Despite the loose constraints, the system always remained very near its target location, even during moves. Figure 14 shows a representative position change from the wing observation position to the contact position. The x, y, and z axes are relative position in the tanker body frame, with x positive out of the nose, y out of the right wing, and z positive down through the tanker belly. The controller moved the target position around the desired path for the position change. The controller on the Learjet was designed to minimize error between the commanded and actual positions, and as such it followed the desired position. At no time was the Learjet more than 6 feet from the targeted position. The major source of position error occurred in the lateral axis for two reasons. First, each leg of the position change (back and down, then across, then forward and up) was accomplished in 30 seconds. The lateral move was greater in distance than the others, requiring a faster rate of the moving target position. More importantly, however, the lateral channel took longer to get the aircraft moving. Unlike the throttles or the elevator, the ailerons did not directly fix lateral error. Instead, they generated roll rate, which over time generated heading change, which over time reduced lateral error. The second time integration required to actually move the aircraft in the desired direction caused a long delay in canceling error. This caused the initial spike in lateral (y) error shown at 40 seconds in Figure 14. The desired target moved away from the Learjet and it took time to get the turn going. The errors that followed were due to error integration and the effects of the target position stopping as it reached the back corner of the maneuver.

Data Basis: Flight Test
Date: 13 Oct 05
Altitude: 10,000 ft
Airspeed: 190 KIAS

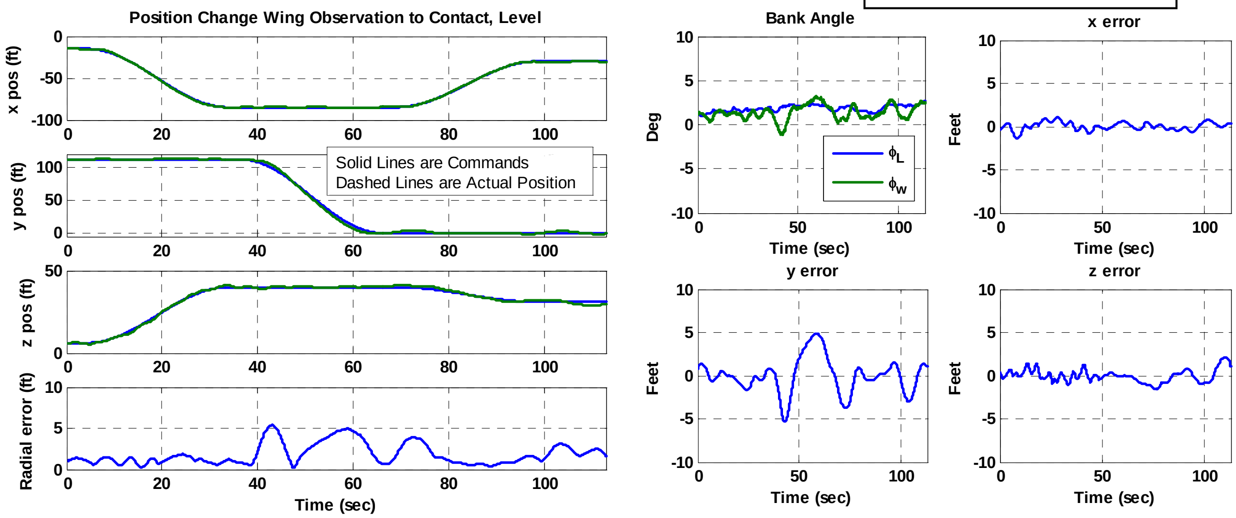



Figure 14. Position Change from Wing Observation to Contact, Level Flight

The system's performance during all position changes was noteworthy. Figure 15**Error! Reference source not found.** shows the maneuver performed in 30 degrees of bank. Some minor additional error was observed, but overall the system performance was solid. The system followed the path better than a human pilot could, though following the exact path during a position change is not critical (as long as the pilot can get to the required position safely, precision along the way doesn't matter—to a point).

Data Basis: Flight Test
Date: 14 Oct 05
10,000 ft, 190 KIAS

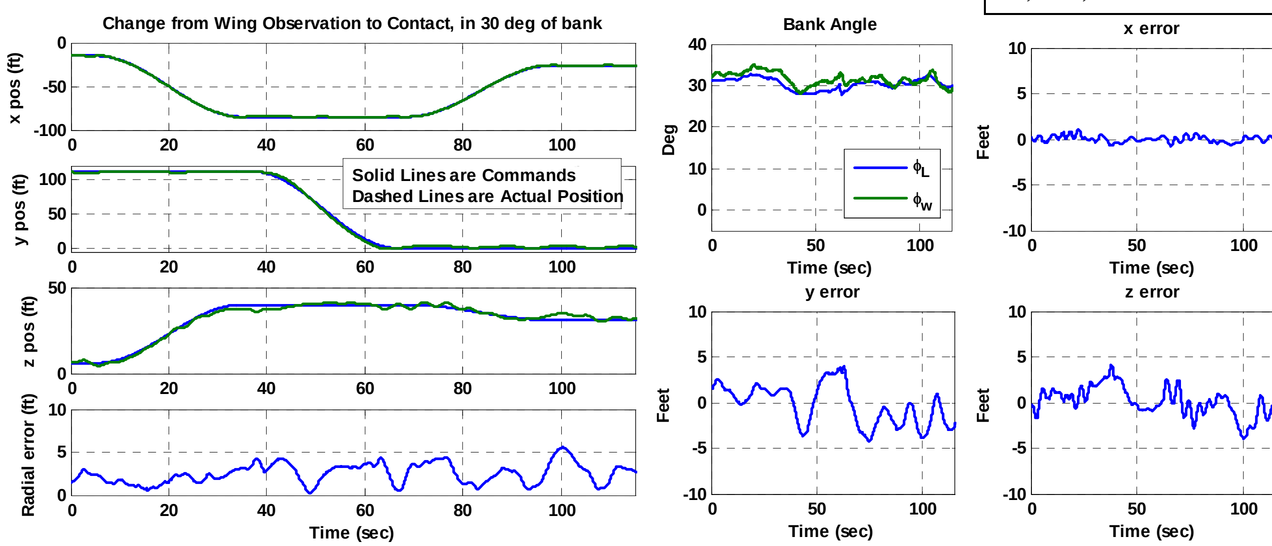



Figure 15. Position Change in 30 degrees of Bank

Turns initiated during a position change added an element of difficulty, as the controller had to deal simultaneously with changing position and formation geometry. For instance, Figure 16 shows a turn initiated at 60 seconds which was overshot to 19 degrees of bank just as the Learjet reached the "back corner" of the position change (the most inopportune time for a turn into the receiver). This effectively increased the amount of closure the wing aircraft had to deal with, while tracking a changing bank angle and a moving position target. As shown, the dynamics of turning to 15 degrees of bank during position changes were small enough not to significantly affect performance.

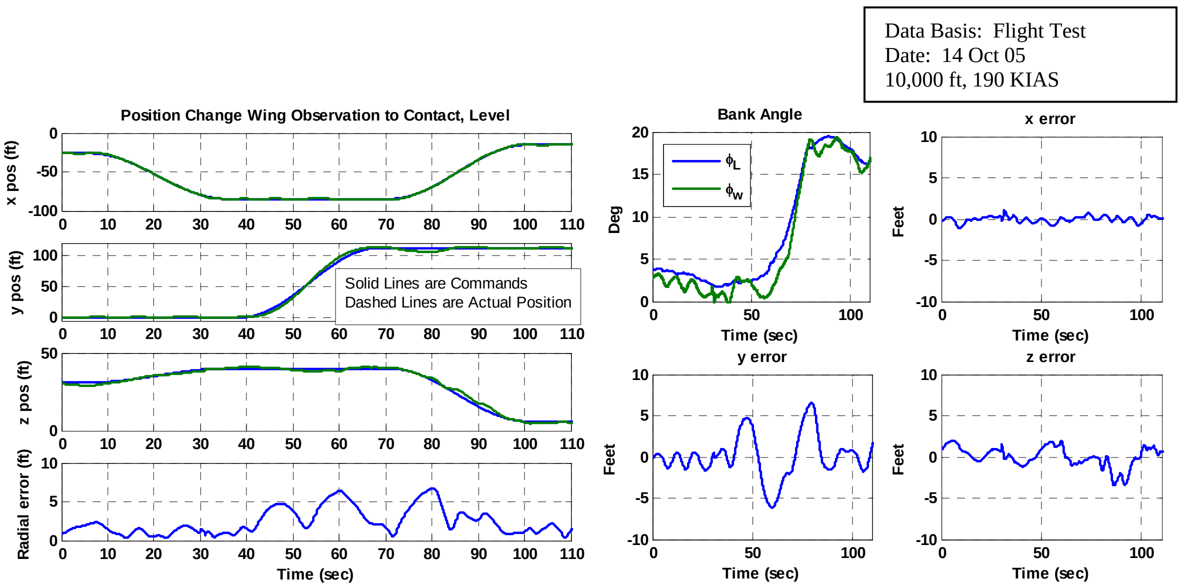



Figure 16. Roll Initiated During Position Change

There were three anomalies noted and corrected by the test crew during position change testing. None of them impacted the performance of the system during normal operations. The first was intermittent failure of the position sequencing. "Horseshoe Logic" was installed for protection against mis-keying a "go to" position selection. For instance, if the aircraft was in the wing observation position and the contact position was selected to "go to", the aircraft should not travel straight there (unacceptable reduction in aircraft separation results). Instead, the aircraft should cycle from wing observation back and down to a "corner" position, across to precontact, and then straight forward and up into contact. The "Horseshoe Logic" automatically scheduled the correct sequence of moves to get to the position selected as "go to". In flight, the logic effectiveness was intermittent. At times, the aircraft would sequence directly to the desired point. In each case, the aircraft would be set up in the same position and the same key sequence was repeated and sometimes it would work correctly, sometimes it wouldn't. The logic sequencing used a memory block which was known by the Calspan crew to have intermittent functionality in the VSS. The memory block logic was also used in a "heading sync" option (installed to sync the lead and wing headings at the beginning of the sortie to compensate for the failed IMU). The sync option should have changed the estimated lead heading when a key was selected by the FTE. Again, success was intermittent, and the key normally would have to be hit three to four times before it worked. The “Horseshoe Logic” was ground tested in the simulator, and the actual software in the aircraft was removed and tested. The software was functionally correct, and the memory block function in the VSS was suspected as the cause of intermittent operation. The “Horseshoe Logic” only existed as an increase in automation. The test team continued the sorties without it (manually commanding the “go to” for each leg of the maneuver).

The second and third unusual occurrences were found during robustness testing for the system. When the aircraft was moving from the wing observation position backward to the “corner” position, the lead aircraft initiated a 30 degree banked turn into the Learjet. The geometry change forced the Learjet into a position of excess speed, with the throttles already reduced for the position change. The maneuver led to a divergent longitudinal overshoot. Due to a miscommunication between Calspan and the system designer, the auto-throttle authority was limited to one-half of the full range, centered around the trim throttle condition (neither idle nor max throttle were attainable). The aircraft was unable to maintain its position because a greater range of throttle motion was required for repositioning than for normal station keeping maneuvering. In addition, the error integrator on the longitudinal channel continued to integrate error after the throttle was on the idle stop (or what the system thought was idle). The result was a large delay after the Learjet moved aft and corrected its position before moving the throttles back up, leading to a large correction and overshoot forward this time, and so on. Both errors were corrected in the software.

Figure 17. Position Change over Edwards AFB

# CONCLUSIONS AND RECOMMENDATIONS

All test points were flown and all objectives were met. Overall, the control system met most of its design goals. The controller demonstrated satisfactory performance for aerial refueling in straight and level flight, staying well within a simulated boom envelope in the contact position and also well within safe position tolerances for the pre-contact and the wing observation positions. The controller also demonstrated satisfactory station keeping in all three positions when established in 15 degree banked turns (the design point), and when established in 30 degree banked turns (beyond the design point). However, during the rolling portion of maneuvers, lateral position error detracted from overall performance, potentially causing disconnects from the refueling boom at the beginning and completion of turns when flying in the contact position.

**Reduce lateral errors during rolling maneuvers (R2, page 12).**

The lateral errors varied in magnitude based on the roll rate and abruptness of the simulated tanker, and were exacerbated during rolls to higher bank levels. A portion of this lateral error was due to a malfunctioning throttle servo and an inoperative heading sensor.

**Repair or replace the IMU before further flight test (R1, page 7).**

The large majority of the error, however, was attributed to the system lateral control gains being lowered to 30 percent of the design values. The gains had been lowered in an effort to reduce suspected noise issues. Those issues turned out not to be noise, but rather a GPS problem which was later compensated for. Due to time constraints, however, the gains were not reset to the design values. The configuration of the system actually flown met the objectives of being able to station keep in all positions, but not as well as it could have, or as well as would be required for operational use. If the conditions which detracted from performance are rectified, a considerably higher level of performance may be attained, and the true capability of the controller may be analyzed.

**Repeat rolling maneuver testing with an operative heading system on the lead aircraft, a repaired throttle servo, and the design gains (R3, page 12).**

The controller was also designed to change formation positions during straight and level flight, and during turns to 15 degrees of bank. All position changes were safe and efficient. Turns using 30 degrees of bank, including turns initiated and completed while the Learjet was in between positions were also investigated as a measure of robustness. In one case, a software error artificially limited full throttle authority, causing a loss of station keeping during more aggressive maneuvering. This limitation was found and repaired. In all other cases, the controller correctly compensated for the additional dynamics, and at no time exceeded safe and desirable location limits for air refueling with multiple receivers.

REFERENCES

1. Ross, Steven. *Formation Flight Control for Aerial Refueling*, MS Thesis, AFIT/GE/ENY, School of Engineering, Air Force Institute of Technology (AFIT), Wright-Patterson AFB, OH, to be published March, 2006.

2. *Limited Evaluation of a Relative GPS datalink between two C-12C aircraft (Project "Lost Wingman"),* AFFTC-TIM-05-04, Air Force Flight Test Center, Edwards AFB, CA, June 2005.

3. Peters, Patrick J. *Modification Operational Supplement: C-12C, Serial Number 73-1215*, Department of Defense, Edwards AFB CA, 21 March 2005.

4. Taschner, Michael J. *Modification Flight Manual: C-12C, Serial Number 73-1215*, Department of Defense, Edwards AFB CA, 23 September 2002.

# APPENDIX A – FLIGHT TEST MANEUVER DESCRIPTIONS

Figure 18 illustrates the contact, intermediate, pre-contact, and wing observation positions used during this test. Table A-1 provides detailed descriptions of the evaluation criteria for these positions. Table A-2 describes the transitions between the positions.

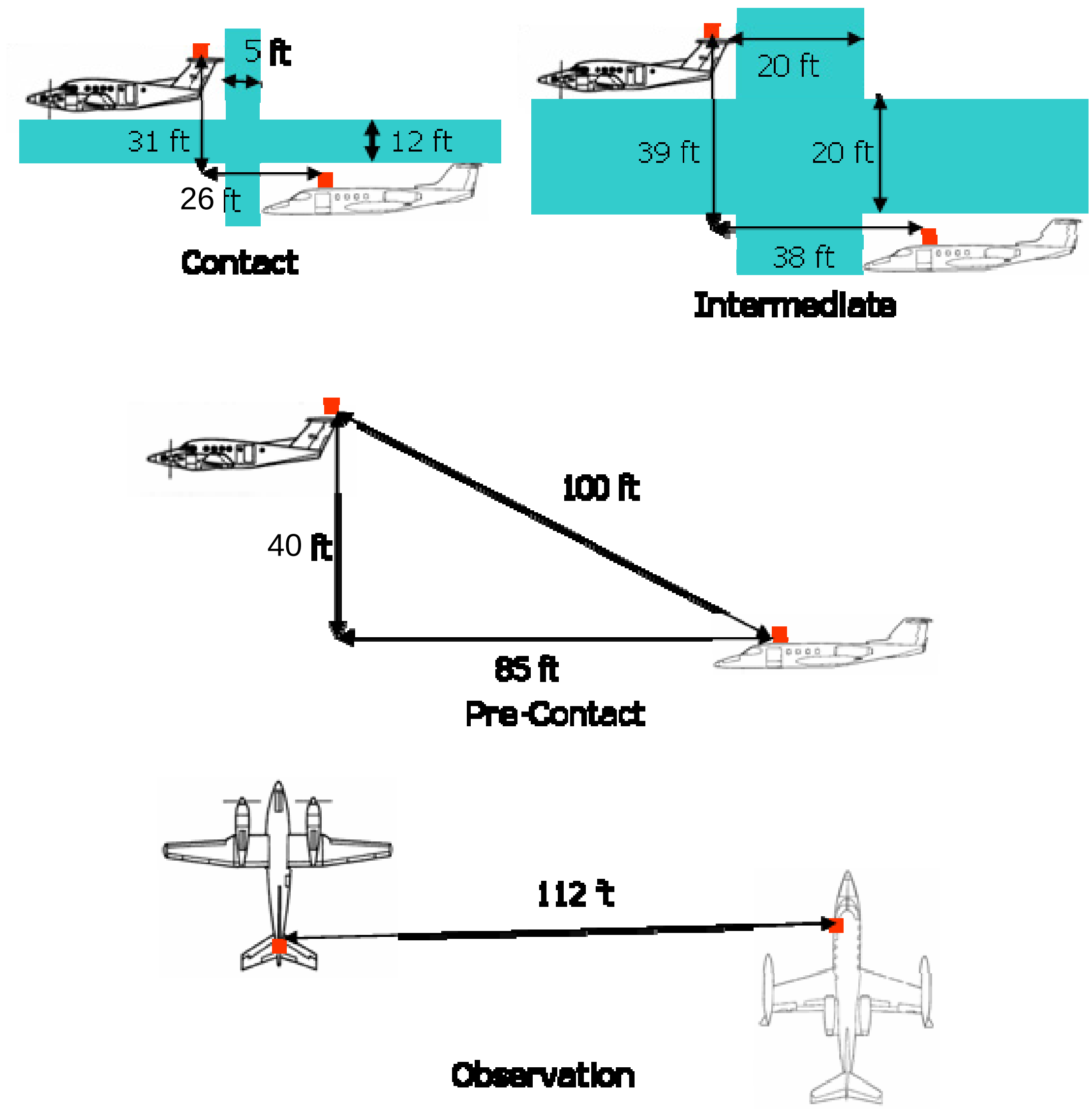



**Figure 18. Formation/Refueling Positions**

Table A-1. Formation/Refueling Position Descriptions

| **Position** | **Description** (distances are antenna to antenna) LJ-25 antenna is 15 feet behind the nose and C-12C antenna is 3 feet forward from the back of the tail. | **Criteria** |
|---|---|---|
| Contact | 31 ft down and 26 ft behind the C-12C. Nose-tail and vertical separation maintained. | KC-135 Boom Limits: Roughly -7 ft - +5 ft longitudinally, +/- 8 ft laterally. +/-9 ft vertically |
| Intermediate | Not an actual refueling position. Used only for build-up testing prior to moving to contact position. 38 feet back and 39 feet down from the C-12C.<br>Nose-tail and vertical separation maintained. | No station keeping limits apply. Used only as buildup prior to moving into contact position. |
| Pre-contact | 40 ft down and 85 ft behind the C-12C. Nose-tail and vertical separation maintained. | +/- 35 ft longitudinally and laterally. No higher than 10 ft below the C-12C and no lower than 50 ft below the C-12C.<br>+/- 65 ft laterally. |
| Observation | 112 ft laterally, 5 feet aft, and 6 ft down. Wing tip separation maintained. | +/-10 ft laterally, and +/- 35 ft longitudinally. |

Table A-2. Formation/Refueling Position Changes

| **Maneuver** | **Description** |
|---|---|
| Observation to Pre-contact | Maneuver aft to ensure antenna separation of approximately 85 feet and descend to establish the trail aircraft 40 feet below the lead aircraft. Then move laterally to arrive in the pre-contact position directly behind the lead aircraft. Rate specified by the test team (initially one minute for the complete maneuver). |
| Pre-contact to Contact | Maneuver up and forward to the contact position at a rate specified by the test team (initially 30 seconds for the complete maneuver) |
| Observation to Contact | Combination of the previous two maneuvers at a rate specified by the test team (initially 90 seconds for the complete maneuver) |
| Pre-contact to Intermediate | Maneuver up and forward to the intermediate position at a rate specified by the test team (initially 30 seconds for the complete maneuver). Test build up only. |
| Intermediate to Pre-Contact | Maneuver down and aft to the pre-contact position at a rate specified by the test team (initially 30 seconds for the complete maneuver). Test build up only. |
| Contact to Pre-contact | Maneuver aft and down to the pre-contact position at a rate specified by the test team (initially 30 seconds for the complete maneuver) |
| Pre-contact to Observation | Maneuver laterally to obtain 112 feet lateral separation. Then move forward and climb to the observation position. |
| Contact to Observation | Combination of the previous two maneuvers at a rate specified by the test team (initially 90 seconds for the complete maneuver) |

# APPENDIX B – PARAMETER LIST

The following tables list the data elements recorded in the system.

**Table B-1.  Lead Aircraft Parameters**

| Number | Parameter Name | System | Units | Resolution | Sample Rate (Hz) | Media |
|---|---|---|---|---|---|---|
| 1 | IRIG Time | DAS | Sec | 0.001 | 1000 | 8mm Tape |
| 2 | Event | DAS | - | 1 | - | 8mm Tape |
| 3 | Indicated Airspeed | DAS | Knots | 1 | 10 | 8mm Tape |
| 4 | Indicated MSL Altitude | DAS | Feet | 1 | 10 | 8mm Tape |
| 5 | Angle of Attack | DAS | Deg | 0.04 | 76.88 | 8mm Tape |
| 6 | Angle of Sideslip | DAS | Deg | 0.04 | 76.88 | 8mm Tape |
| 7 | Outside Air Temperature | DAS | $^{o}$C | 0.01 | 10 | 8mm Tape |
| 8 | Roll Angle | DAS | deg | 0.03 | 76.88 | 8mm Tape |
| 9 | Pitch Angle | DAS | deg | 0.02 | 76.88 | 8mm Tape |
| | | | | | | |
| 10 | Time of Day | GAINR | HMS | 0.001 | 10 | PCMCIA |
| 11 | Time of Day | GAINR | sec | 0.001 | 10 | PCMCIA |
| 12 | Latitude | GAINR | deg | 0.00001 | 10 | PCMCIA |
| 13 | Longitude | GAINR | deg | 0.00001 | 10 | PCMCIA |
| 14 | Ellipsoid Height | GAINR | feet | 0.1 | 10 | PCMCIA |
| 15 | MSL Altitude | GAINR | feet | 0.1 | 10 | PCMCIA |
| 16 | Ambient Temperature | GAINR | $^{o}$C | 0.1 | 10 | PCMCIA |
| 17 | True Airspeed | GAINR | ft/s | 0.1 | 10 | PCMCIA |
| 18 | Ψ - PSI - Angle WRT North | GAINR | deg | 0.1 | 10 | PCMCIA |
| 19 | Θ - THETA - Pitch Angle | GAINR | deg | 0.1 | 10 | PCMCIA |
| 20 | Φ - PHI – Roll Angle | GAINR | deg | 0.1 | 10 | PCMCIA |
| 21 | X Pos - N,E,U Coordinates | GAINR | feet | 0.1 | 10 | PCMCIA |
| 22 | Y Pos - N,E,U Coordinates | GAINR | feet | 0.1 | 10 | PCMCIA |
| 23 | Z Pos - N,E,U Coordinates | GAINR | feet | 0.1 | 10 | PCMCIA |
| 24 | X Pos - Geocentric | GAINR | feet | 0.1 | 10 | PCMCIA |
| 25 | Y Pos - Geocentric | GAINR | feet | 0.1 | 10 | PCMCIA |
| 26 | Z Pos - Geocentric | GAINR | feet | 0.1 | 10 | PCMCIA |
| | | | | | | |
| 27 | GPS Time of week | SUT | sec | 0.001 | 20 | Laptop File |
| 28 | Lead Yaw - Ψ - PSI | SUT | deg | 0.001 | 20 | Laptop File |
| 29 | Lead Pitch - Θ - THETA | SUT | deg | 0.001 | 20 | Laptop File |
| 30 | Lead Roll - Φ - PHI | SUT | deg | 0.001 | 20 | Laptop File |
| 31 | Lead Roll Rate – p | SUT | deg/s | UNK | 20 | Laptop File |
| 32 | Raw GPS Data | SUT | - | N/A | 20 | Laptop File |
| 33 | Transmitted datalink signal | SUT | - | - | 20 | Laptop File |

Note:  DAS data were desired but not required for flight.

**Table B-2. Trail Aircraft Parameters**

| Number | Parameter Name | Units |
|---|---|---|
| 1 | Cockpit communications | Not applicable |
| 2 | Time | Sec |
| 3 | Learjet Heading (psi) | Degrees |
| 4 | Learjet Pitch Angle (theta) | Degrees |
| 5 | Learjet Bank Angle (phi) | Degrees |
| 6 | Learjet Roll Rate (p) | Degrees/sec |
| 7 | Learjet Angle of Attack (alpha) | Degrees |
| 8 | Learjet Angle of Sideslip (beta) | Degrees |
| 9 | Learjet Z-axis acceleration (Nz) | G’s |
| 10 | Learjet Indicated Velocity | KIAS |
| 11 | Learjet Altitude | Feet |
| 12 | Outside air temp | Celsius |
| 13 | C-12 Heading (psi) | Degrees |
| 14 | C-12 Pitch Angle (theta) | Degrees |
| 15 | C-12 Bank Angle (phi) | Degrees |
| 16 | C-12 Roll Rate (p) | Degrees/sec |
| 17 | GPS Differential Vector, North | Feet |
| 18 | GPS Differential Vector, East | Feet |
| 19 | GPS Differential Vector, Down | Feet |
| 20 | Engage Autopilot Command | None |
| 21 | Engage Throttle Command | None |
| 22 | Go To Command | None |
| 23 | Elevator Command | Degrees |
| 24 | Elevator Position | Degrees |
| 25 | Aileron Command | Degrees |
| 26 | Aileron Position | Degrees |
| 27 | Rudder Command | Degrees |
| 28 | Rudder Position | Degrees |
| 29 | Left Throttle Command | Pounds |
| 30 | Left Throttle Position | Pounds |
| 31 | Right Throttle Command | Pounds |
| 32 | Right Throttle Position | Pounds |
| 33 | Speed of Position Change | None |
| 34 | k_xe (proportional gain, throttle) | None |
| 35 | k_xd (derivative gain, throttle) | None |
| 36 | k_xi (integral gain, throttle) | None |
| 37 | k_ye (proportional gain, aileron) | None |
| 38 | k_yd (derivative gain, aileron) | None |
| 39 | k_yi (integral gain, aileron) | None |
| 40 | k_phi_err (cmd vs actual bank angle gain) | None |
| 41 | k_p_lead (feed forward roll rate gain) | None |

| | | |
|---|---|---|
| 42 | k_p_err (cmd vs actual roll rate penalty) | None |
| 43 | k_ze (proportional gain, elevator) | None |
| 44 | k_zd (derivative gain, elevator) | None |
| 45 | k_zi (integral gain, elevator) | None |
| 46 | k_theta (non-equilibrium pitch penalty gain) | None |
| 47 | k_wing_theta_eq (equilib theta estimate) | Deg |
| 48 | k_sas (yaw damper gain) | None |
| 49 | Contact Position x-body axis | Feet |
| 50 | Contact Position y-body axis | Feet |
| 51 | Contact Position z-body axis | Feet |
| 52 | Pre-Contact Position x-body axis | Feet |
| 53 | Pre-Contact Position y-body axis | Feet |
| 54 | Pre-Contact Position z-body axis | Feet |
| 55 | Back Corner Position x-body axis | Feet |
| 56 | Back Corner Position y-body axis | Feet |
| 57 | Back Corner Position z-body axis | Feet |
| 58 | Wing Observation Position x-body axis | Feet |
| 59 | Wing Observation Position y-body axis | Feet |
| 60 | Wing Observation Position z-body axis | Feet |
| 61 | Tanker to Lear Vector, body axis, x | Feet |
| 62 | Tanker to Lear Vector, body axis, y | Feet |
| 63 | Tanker to Lear Vector, body axis, z | Feet |
| 64 | Tanker to Desired Position, body axis, x | Feet |
| 65 | Tanker to Desired Position, body axis, y | Feet |
| 66 | Tanker to Desired Position, body axis, z | Feet |
| 67 | Post Filter Data, C-12 heading (psi) | Degrees |
| 68 | Post Filter Data, C-12 pitch angle (theta) | Degrees |
| 69 | Post Filter Data, C-12 bank angle (phi) | Degrees |
| 70 | Post Filter Data, C-12 roll rate (p) | Degrees/sec |
| 71 | Post Filter Data, Tanker to Lear, North | Feet |
| 72 | Post Filter Data, Tanker to Lear, East | Feet |
| 73 | Post Filter Data, Tanker to Lear, Down | Feet |


Figure 19.  Contact Position

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# APPENDIX C – REPRESENTATIVE PERFORMANCE PLOTS

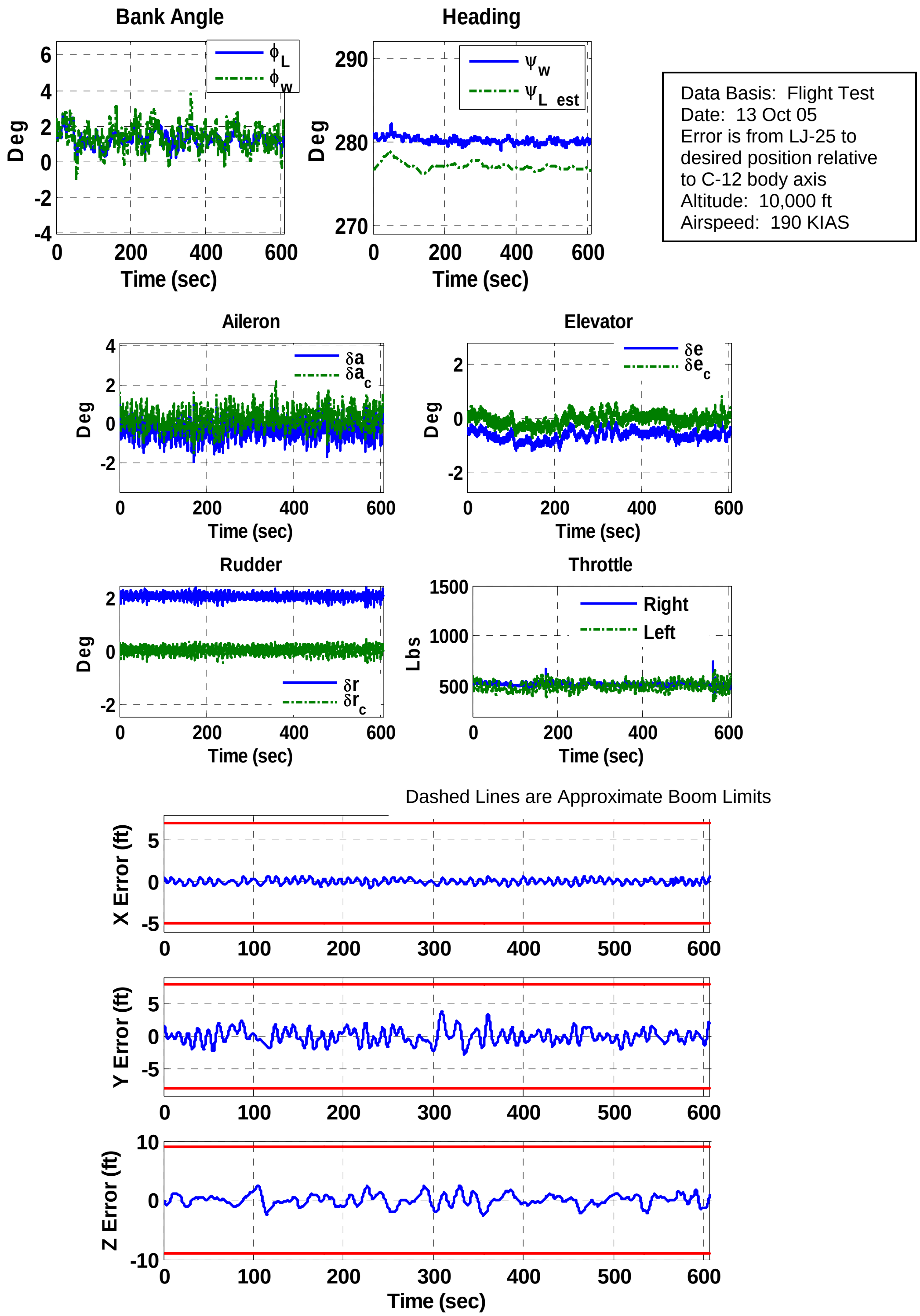


**Figure 20. Ten Minutes in Contact Position, Straight and Level**

In positions other than contact, the boom position limits have been removed.

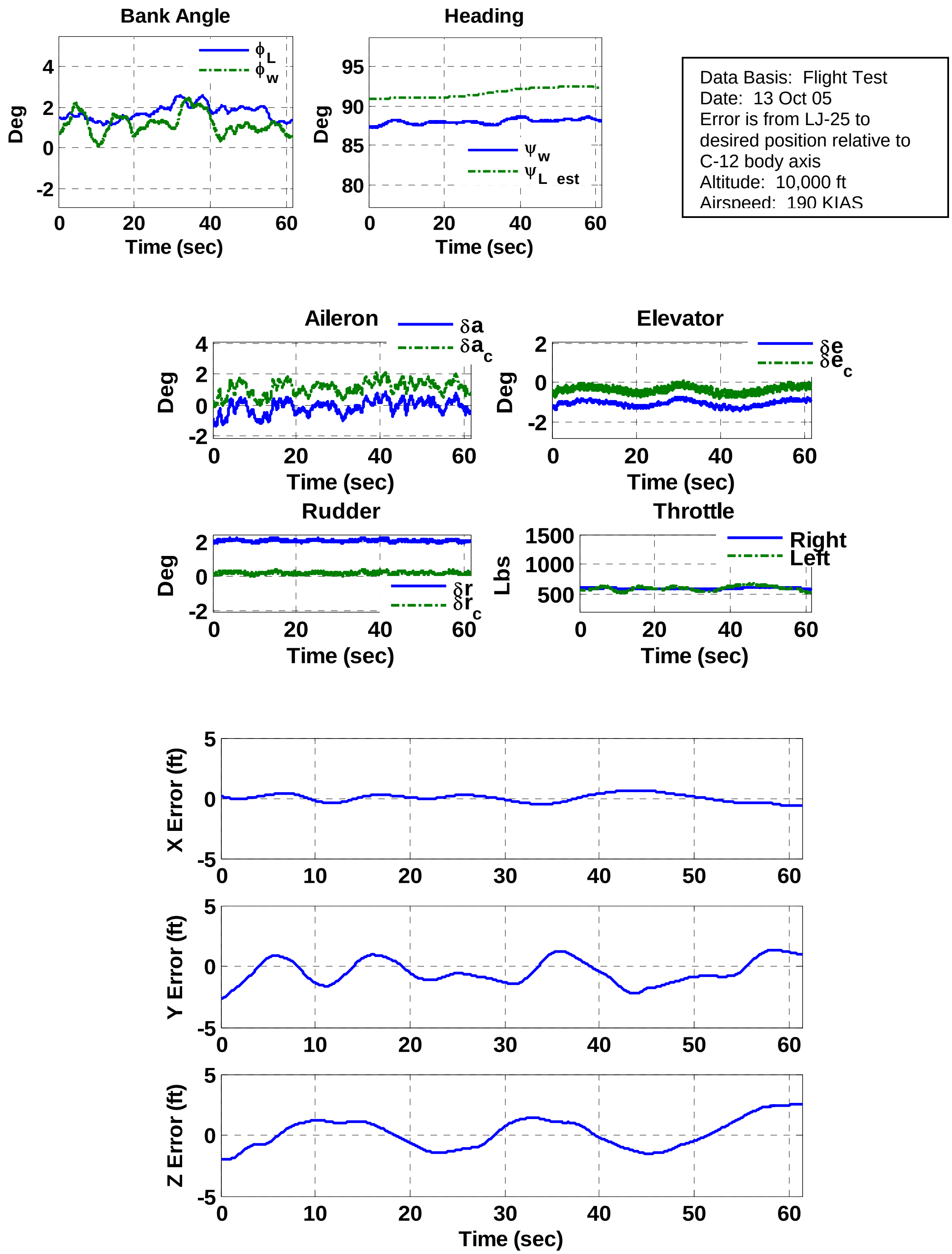


**Figure 21. Maneuver 6:5. Precontact, Straight and Level.**

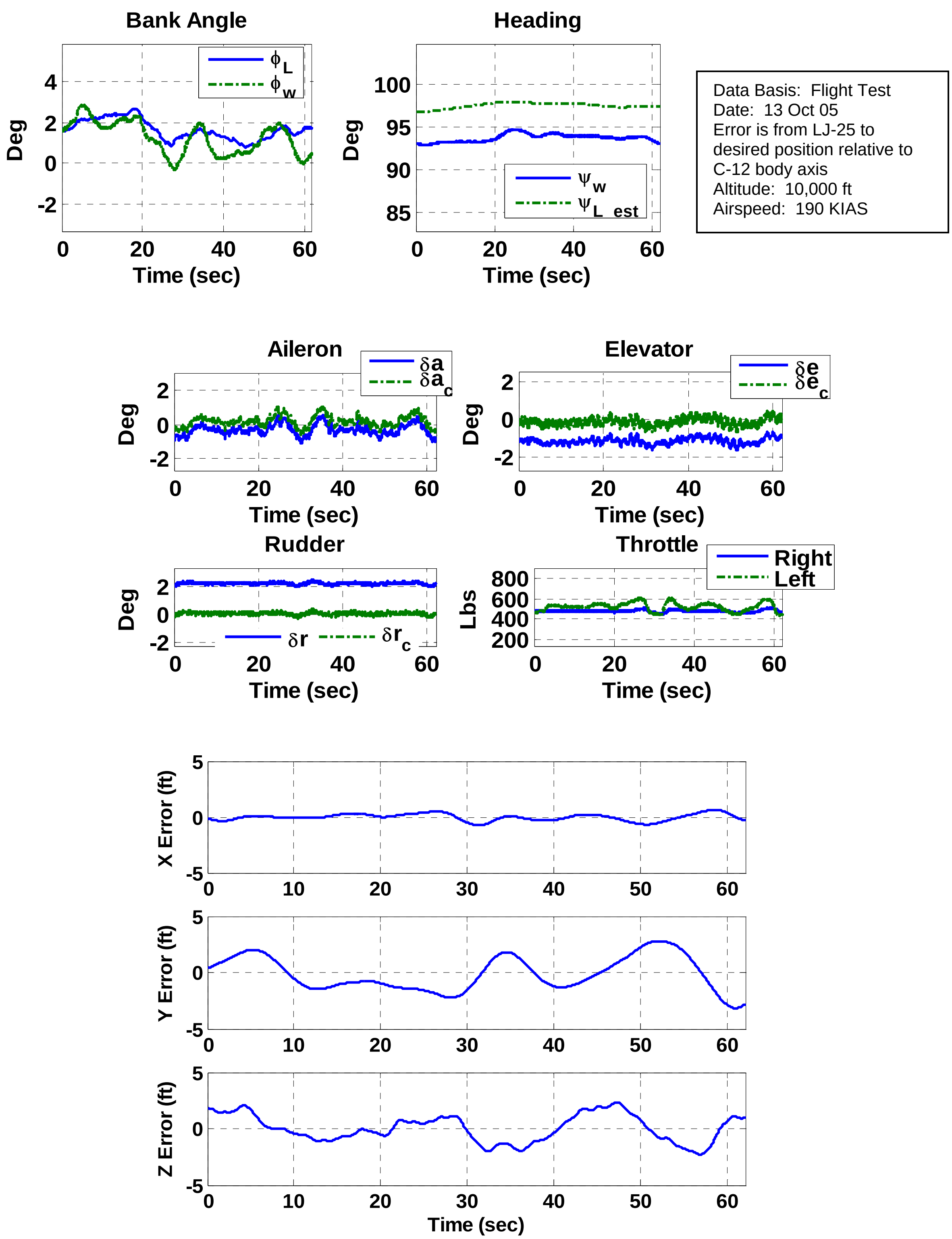


**Figure 22. Maneuver 6:23. Wing Observation, Straight and Level.**

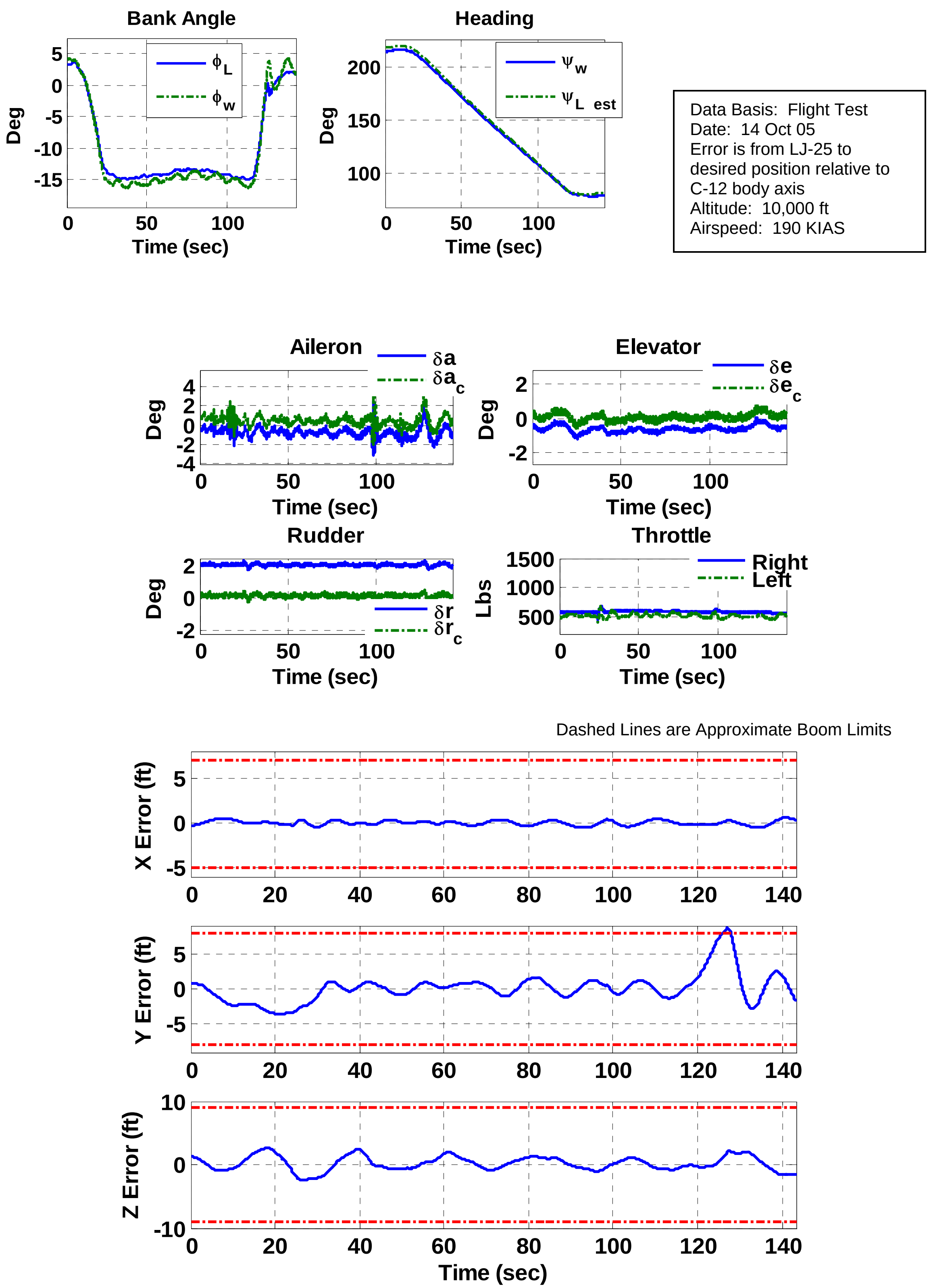


**Figure 23. Maneuver 7:16. Contact 15 deg Bank Turn**

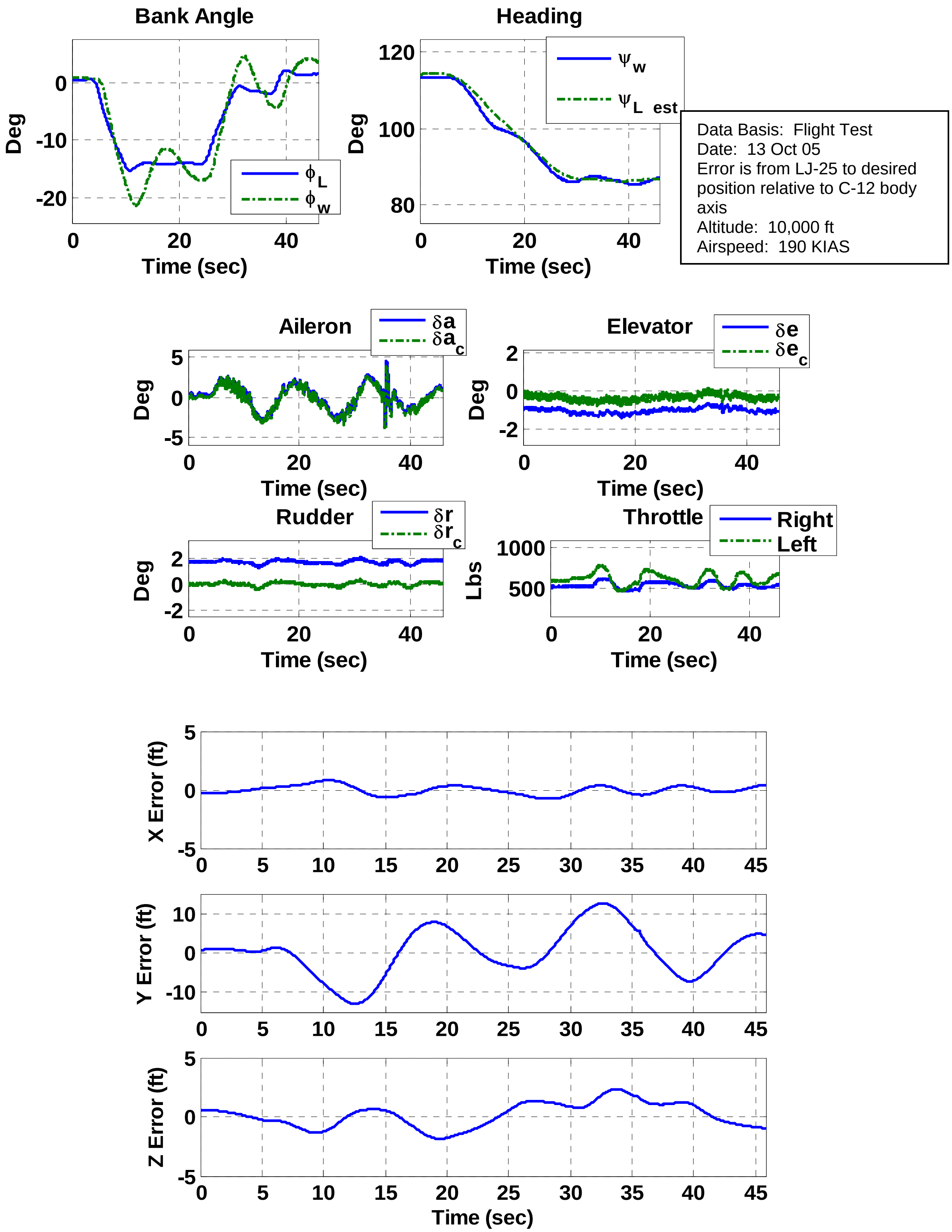


**Figure 24. Maneuver 6:10. Precontact, 15 deg Bank Turn.**

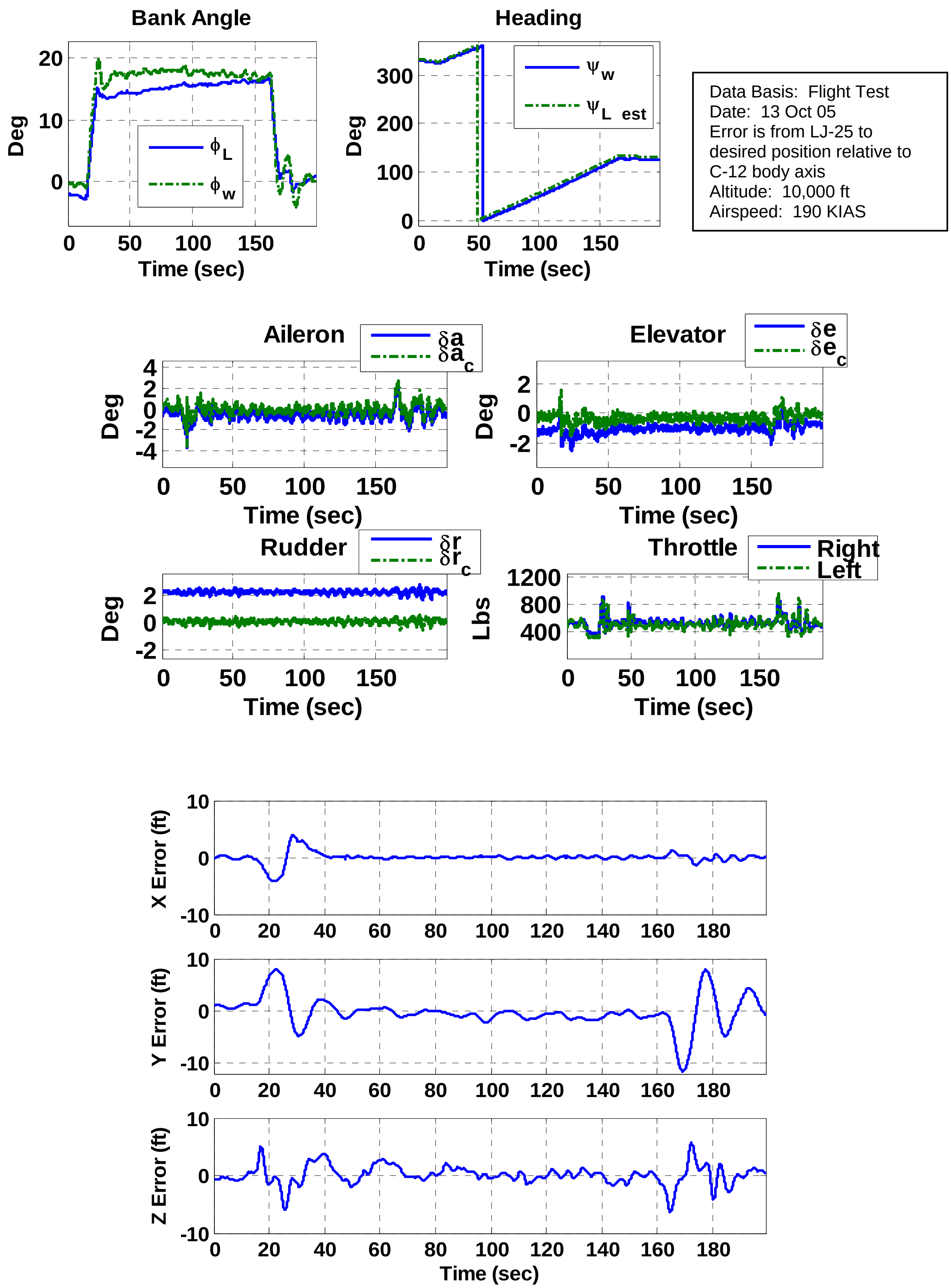


**Figure 25. Maneuver 6:25. Wing Observation, 15 deg Bank**

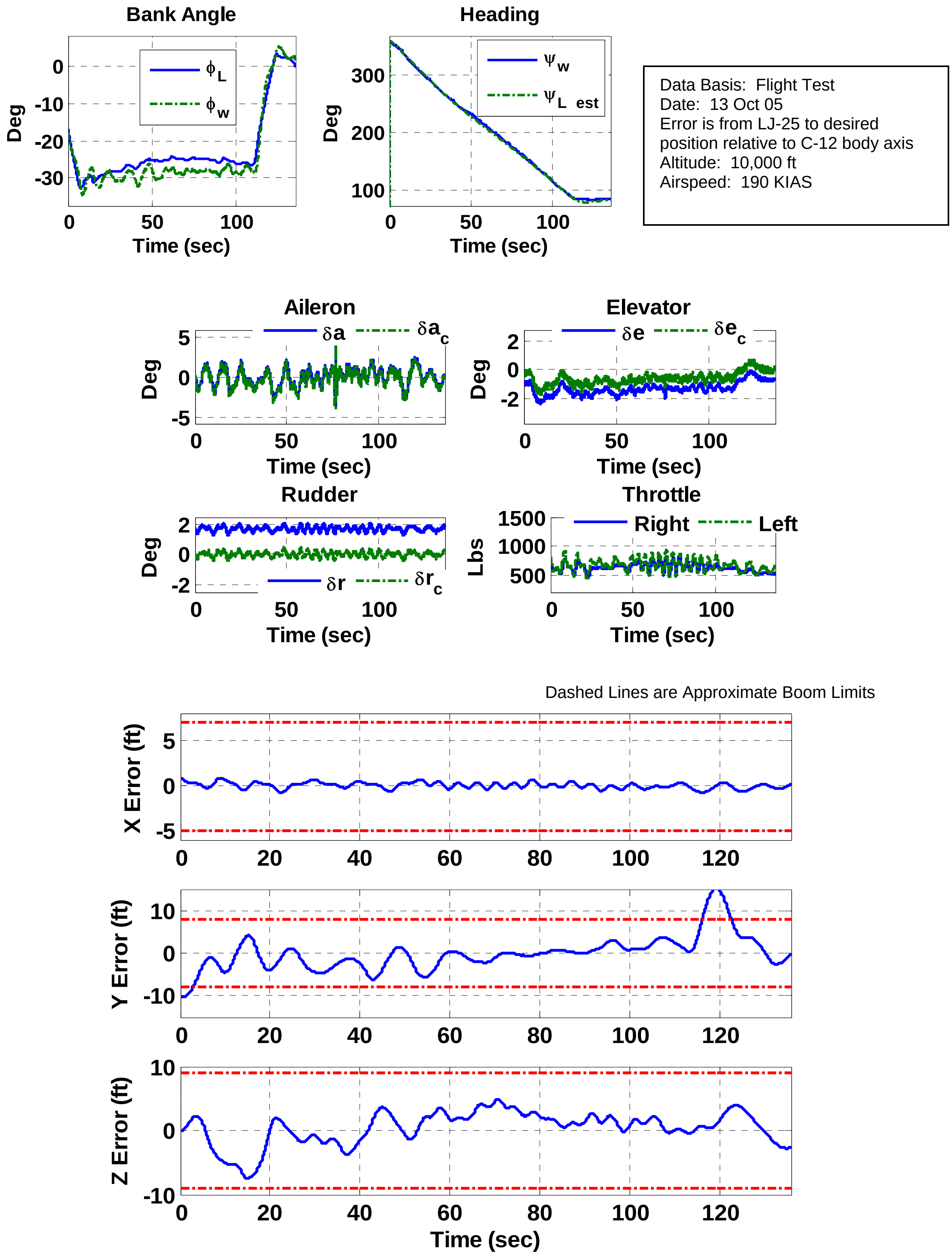


**Figure 26. Maneuver 6:14. Contact 30 deg Bank Turn**

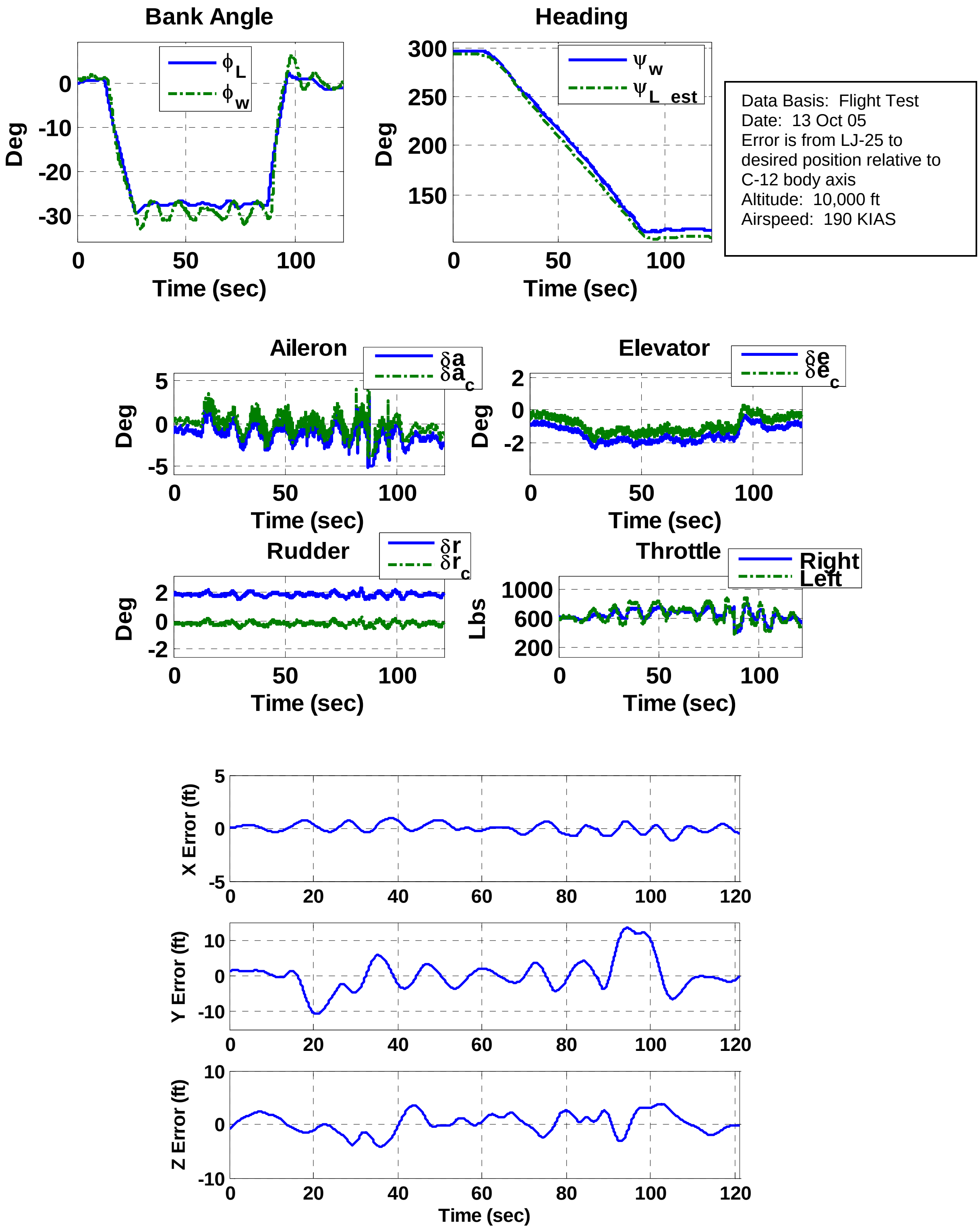


**Figure 27. Maneuver 6:7. Precontact, 30 deg Bank Turn.**

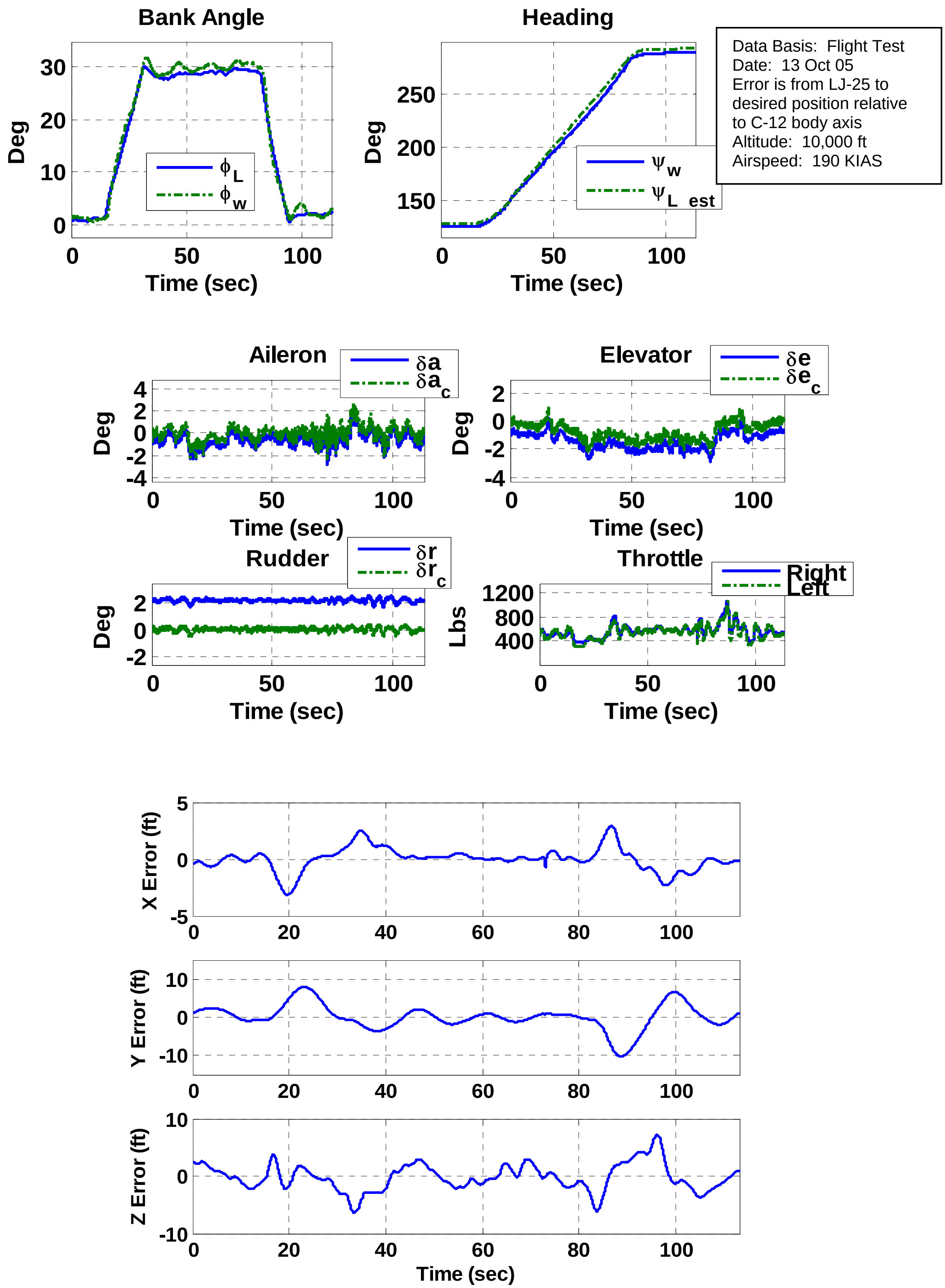


**Figure 28. Maneuver 6:26. Wing Observation, Right Turn with 30 deg of Bank.**

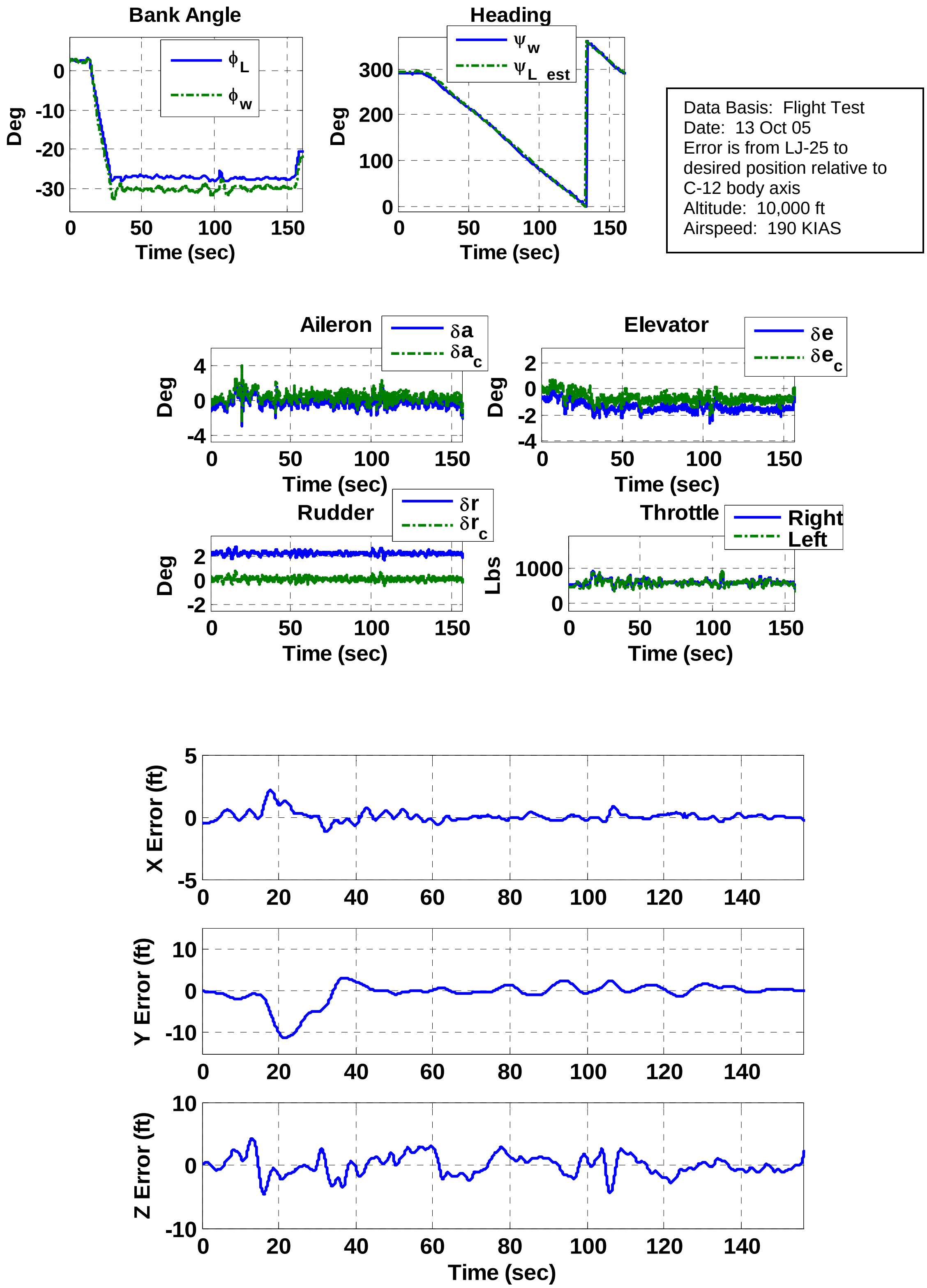


**Figure 29. Maneuver 6:27. Wing Observation Position, Left Turn with 30 deg Bank.**

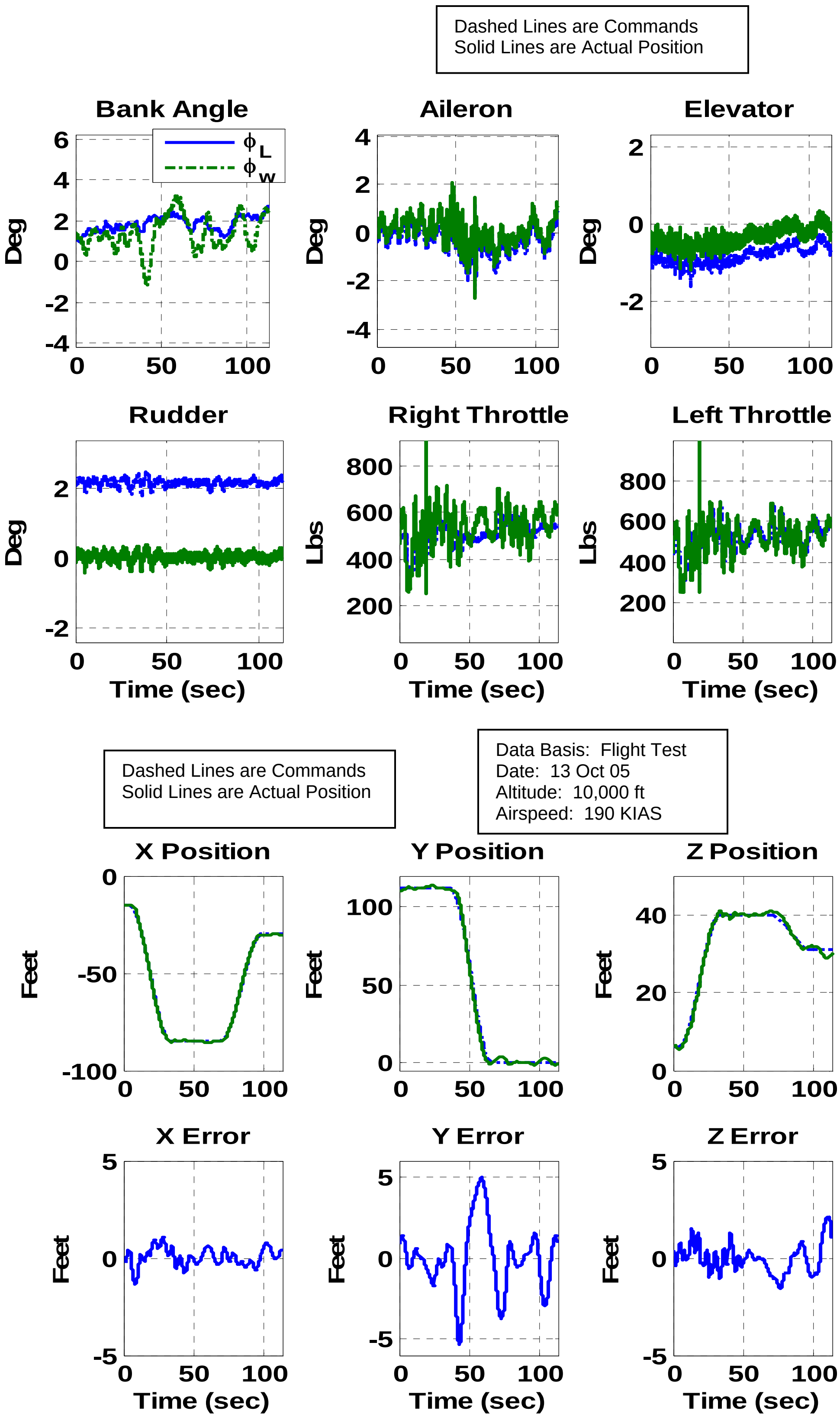


**Figure 30. Maneuver 6:30. Position Change from Wing Obs to Contact, Level.**

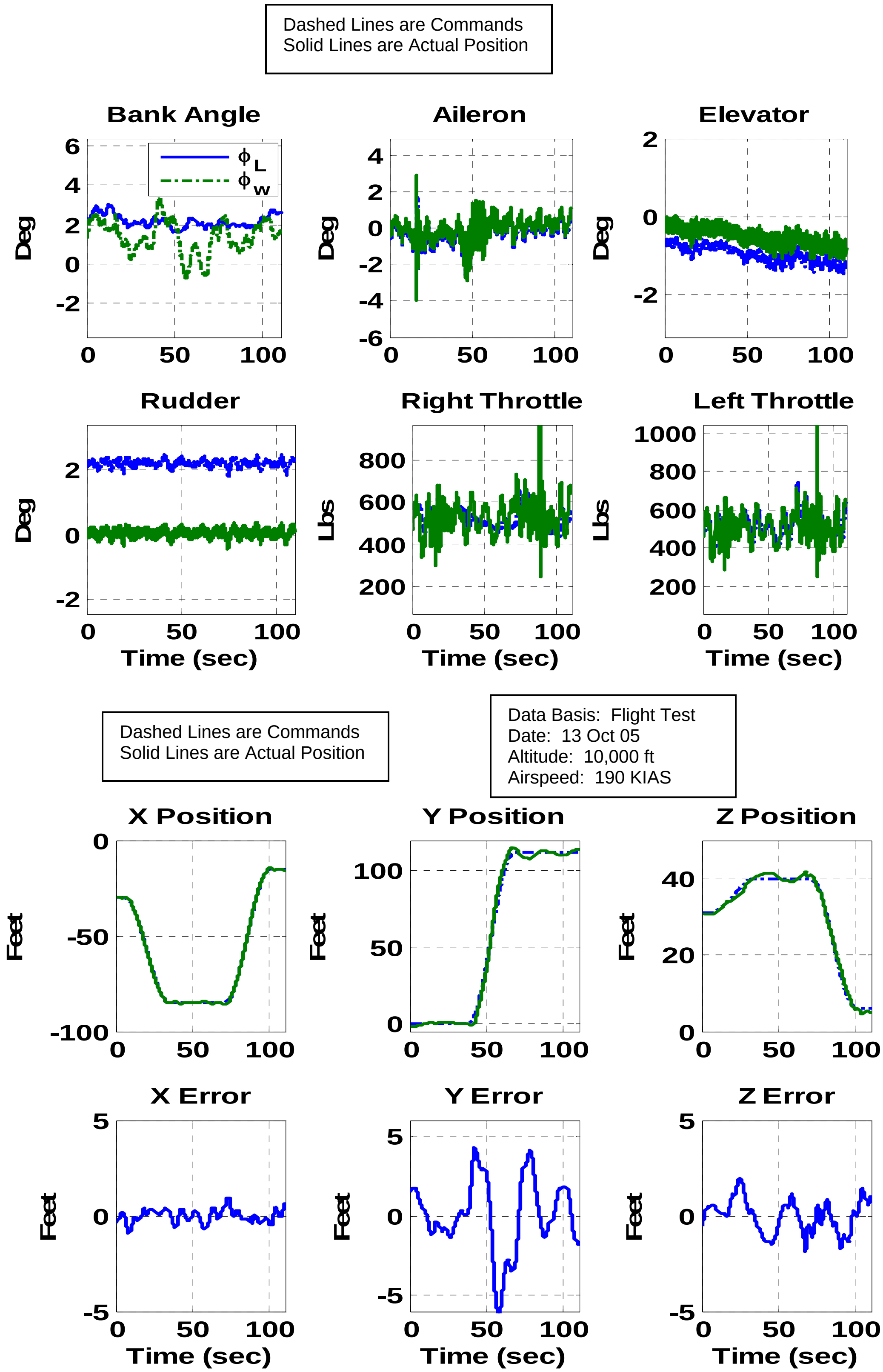


**Figure 31. Maneuver 6:28. Position Change from Contact to Wing Observation, Level.**

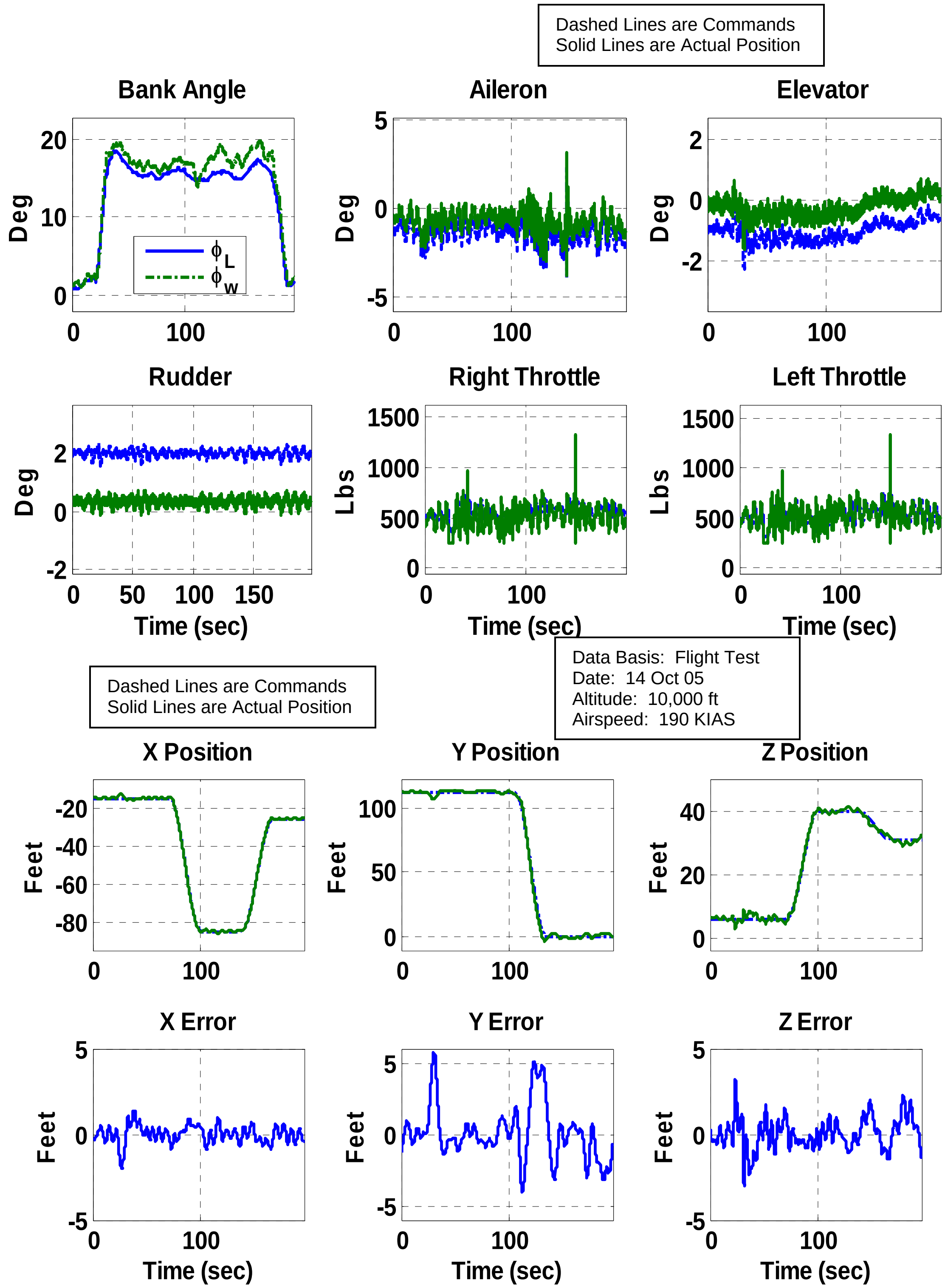


**Figure 32. Maneuver 7:5. Position Change from Wing Observation to Contact in 15 deg Right Bank.**

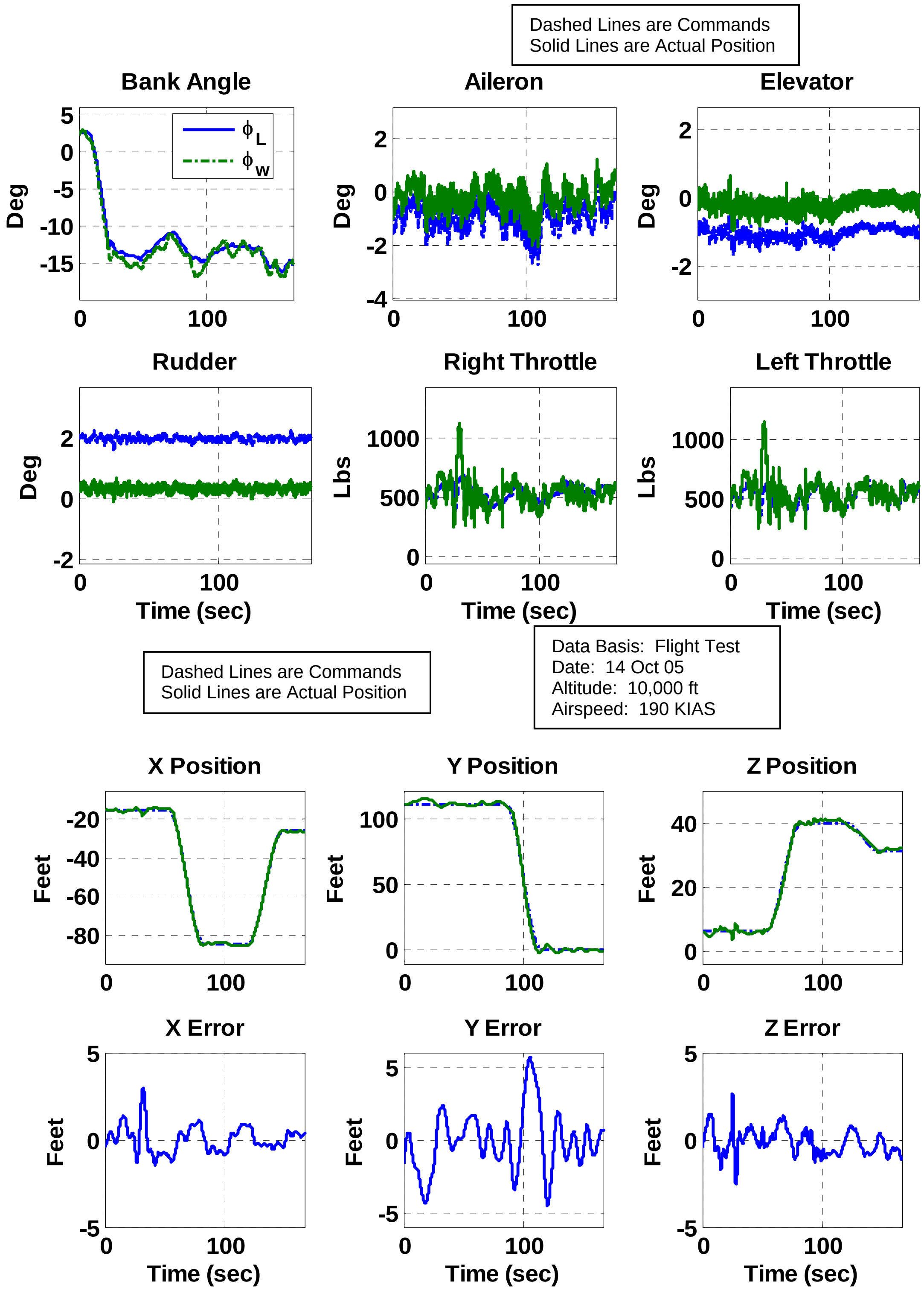


**Figure 33. Maneuver 7:6. Position Change from Wing Observation to Contact in 15 deg of Left Bank.**

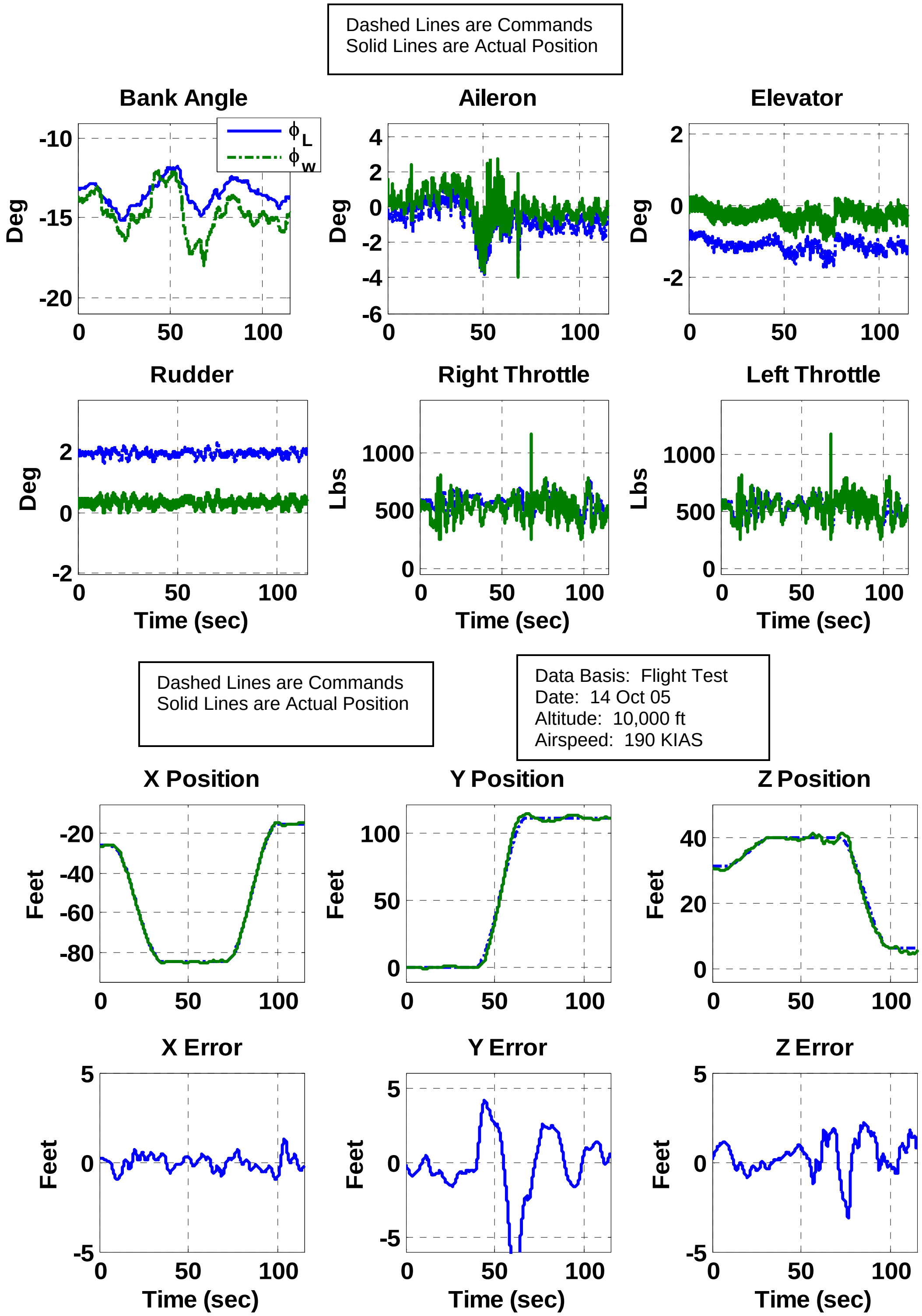


**Figure 34. Maneuver 7:7. Position Change from Contact to Wing Observation in 15 deg Bank.**

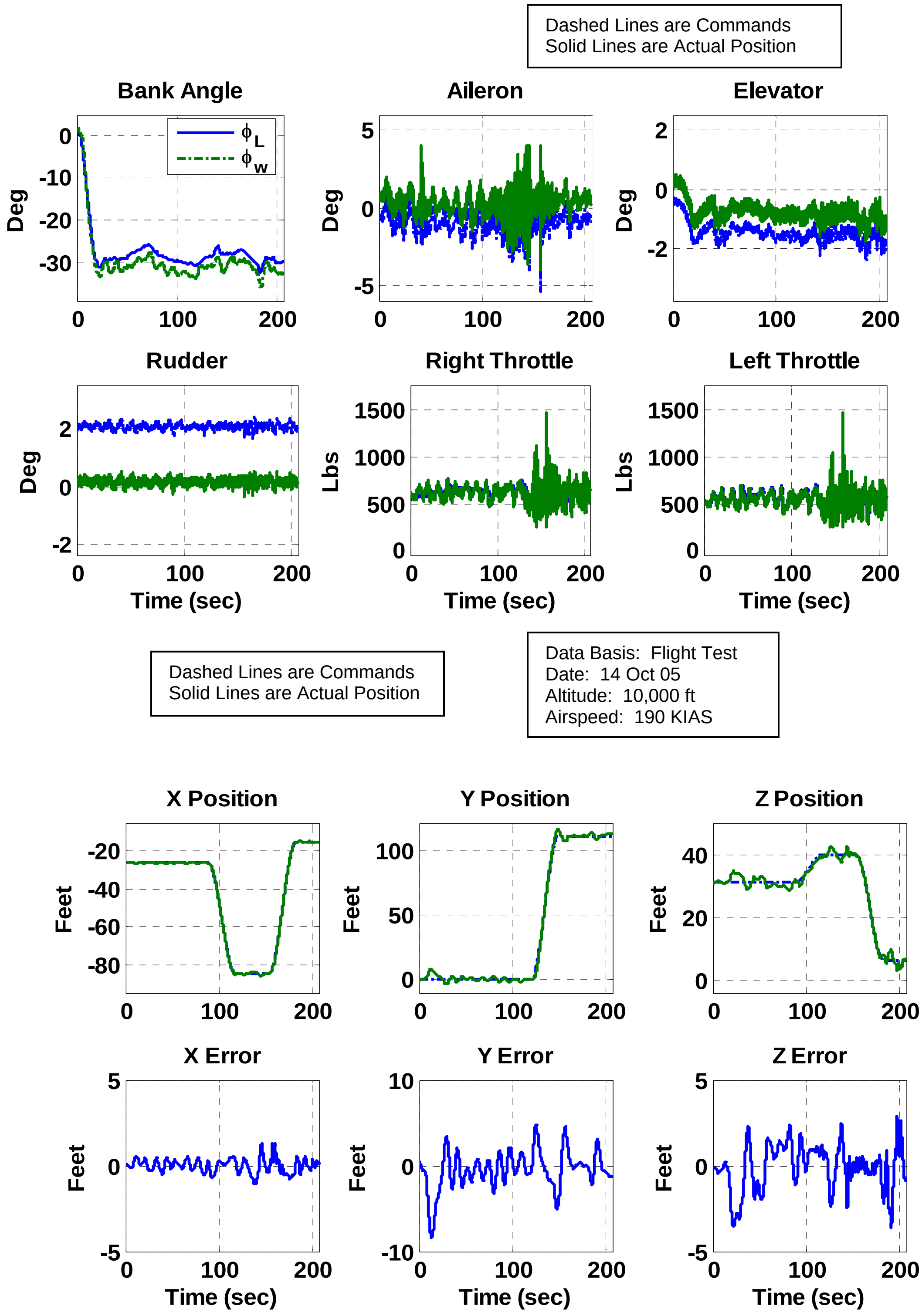


**Figure 35. Maneuver 7:17. Roll to 30 deg Bank, Postition Change from Contact to Wing Observation.**

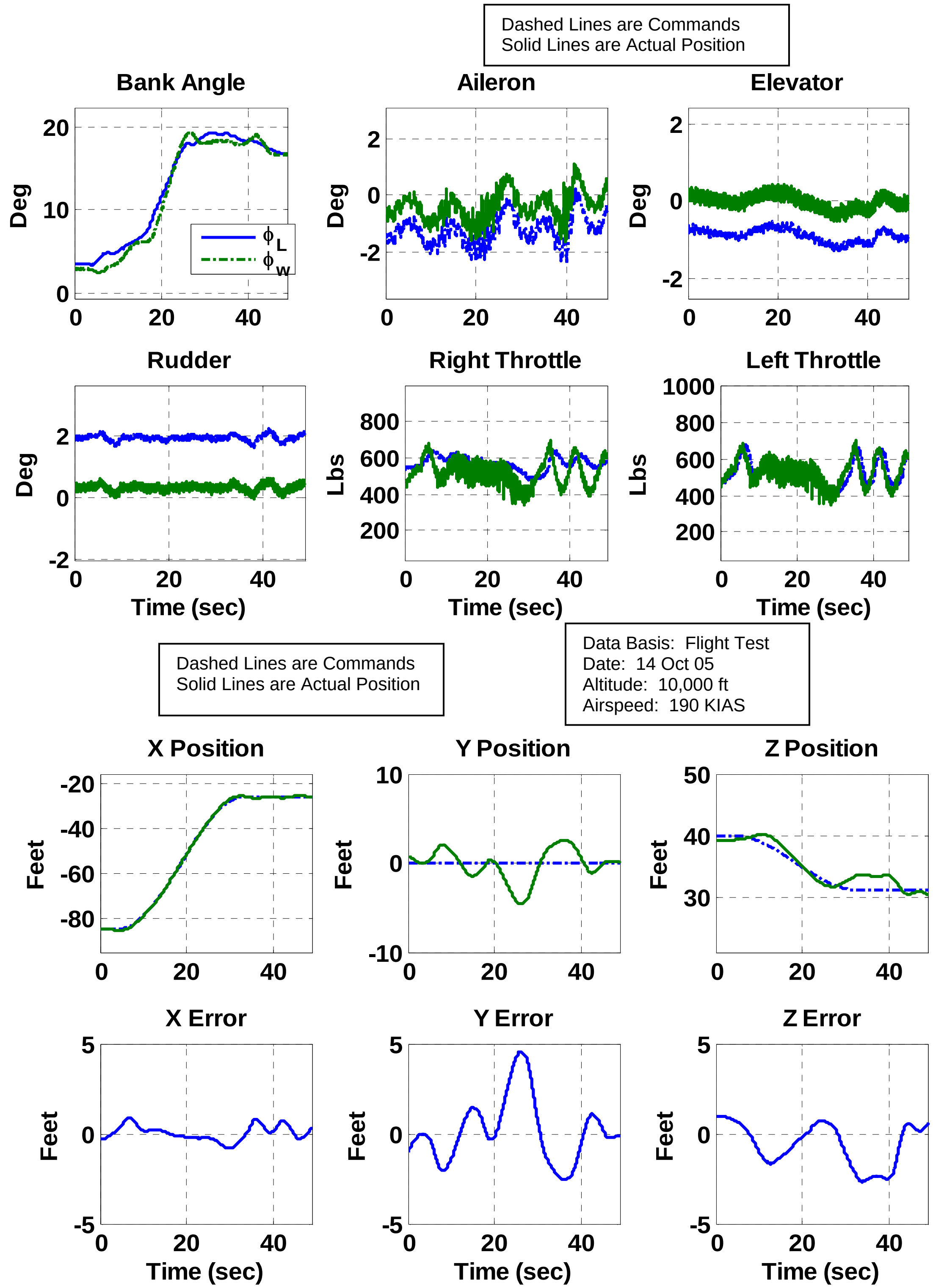


**Figure 36. Maneuver 7:12. Turn Initiated and Stopped while Moving from Precontact to Contact.**

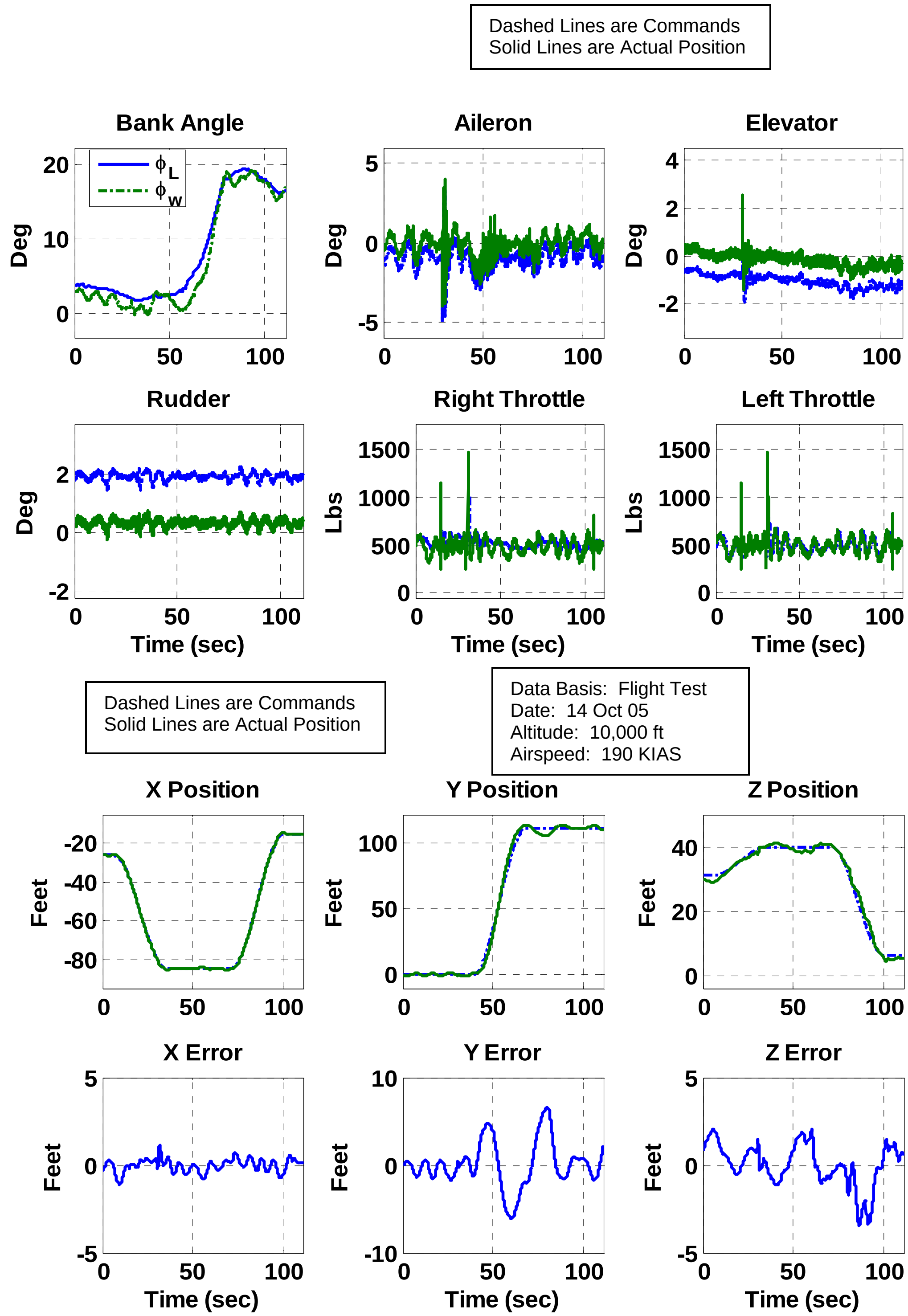


**Figure 37. Maneuver 7:13. Position Change from Contact to Wing Observation, with Roll at "Back Corner".**

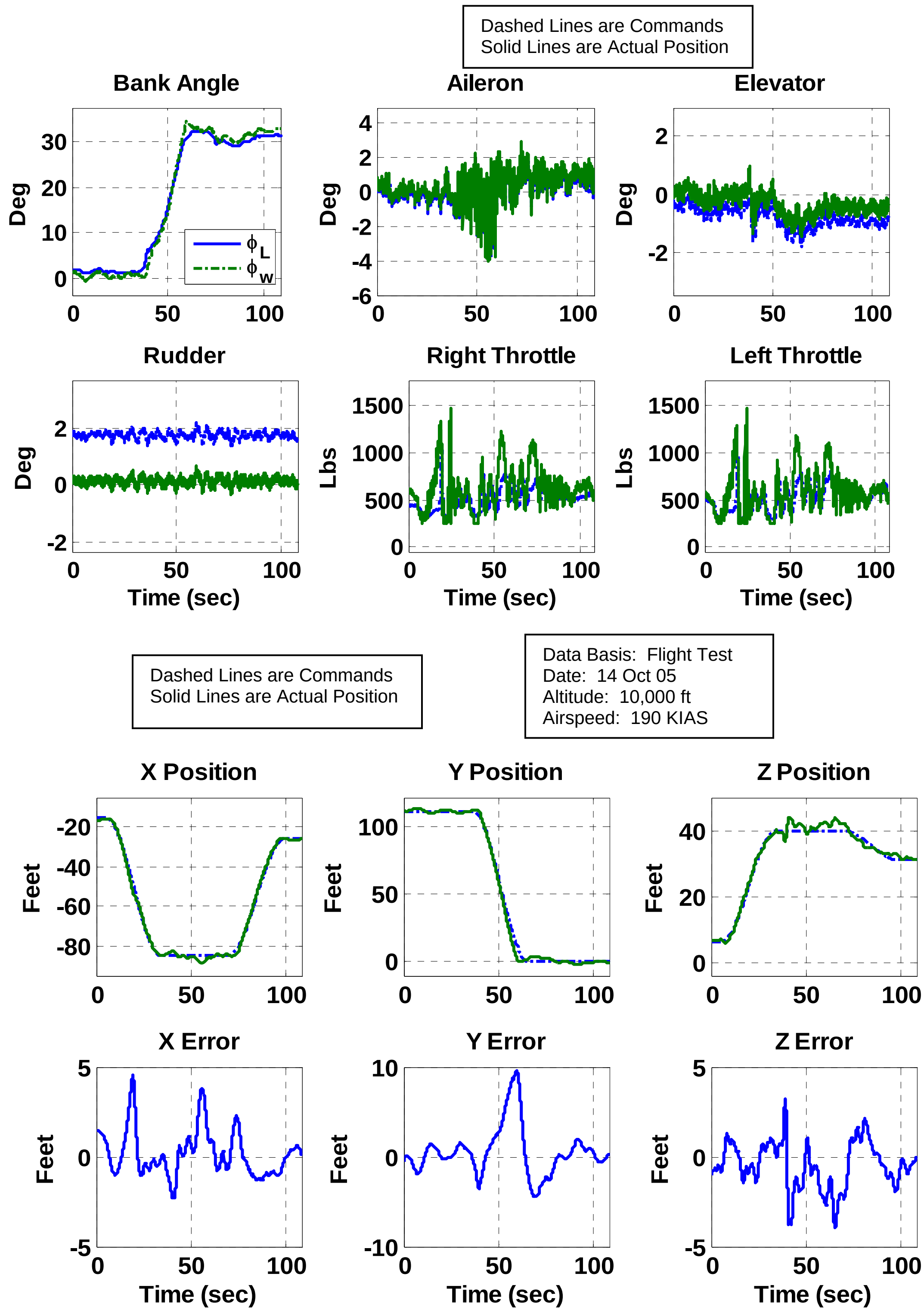


**Figure 38. Maneuver 7:24. Position Change From Wing Observation to Contact with 30 deg Roll into the Wingman at the "Back Corner".**


Figure 39.  Wing Observation Position

# APPENDIX D – LIST OF ACRONYMS

| | |
|---|---|
| AAR | Automated Aerial Refueling |
| AFB | Air Force Base |
| AFFTC | Air Force Flight Test Center |
| AFFTCI | Air Force Flight Test Center Instruction |
| AFIT | Air Force Institute of Technology |
| AFIT/ENG | Air Force Institute of Technology Department of Electrical & Computer Engineering |
| AFIT/SYE | Air Force Institute of Technology Department of Systems Engineering |
| °C | Degrees Celsius |
| COMSEC | Communications Security |
| DAS | Data Acquisition System |
| DGPS | Differential Global Positioning System |
| EMI | Electro-Magnetic Interference |
| FTE | Flight Test Engineer |
| GAINR | GPS Aided Inertial Reference |
| GPS | Global Positioning System |
| Hz | Hertz |
| IMU | Inertial Measurement Unit |
| J-UCAS | Joint Unmanned Combat Aerial System |
| KIAS | Knots Indicated Airspeed |
| KEYMAT | Keying Material |
| MEMS | Micro-Electro-Mechanical System |

| | |
|---|---|
| MFM | Modification Flight Manual |
| RPM | Revolutions Per Minute |
| SLUF | Straight and Level Flight |
| SUT | System Under Test |
| TMP | Test Management Project |
| TPS | Test Pilot School |
| USAFTPS | United States Air Force Test Pilot School |
| VSS | Variable Stability System |

Figure 40.  View from Learjet

.

# APPENDIX E – LESSONS LEARNED

MODELING AND SIMULATION—The impact of modeling and simulation for the success of this project cannot be overstated. Several complete "show stoppers" occurred which were overcome with software fixes and patches. The heading system hardware failure was overcome with a heading estimator, created in simulation using the flight test data from the first two flights. The filtering system was completely restructured, and without these changes the system could not be even connected to the flight controls on the ground. This was also accomplished with an active model. Gain changes were made, which required simulation for tuning and for flight safety. The DGPS problem of missing an update every second was compensated for by using software, which was refined and corrected in the model before implementation. Without a simulator and the ability to modify the controller as errors were found, the test project would never have flown. **For a test project involving new software, having a solid model that has the capability to be modified with new fixes is essential.**

SYSTEM FLEXIBILITY**—**The ability to change the system during and between tests was critical. For the first flight, rudimentary filter tuning was accomplished with several filter options during ground operations. Every input to the system was isolated by hard coding all other inputs to constants. Filter levels on the active channel were then decreased until noise was noticeable in the flight controls. The filter was then increased slightly on that channel, and the next channel was turned on. In flight, both filter levels and some gains required adjustment. Had time permitted, more "fine tuning" of the controller gains would have been the highest priority for the test team. Though simulation was accurate, it was difficult to visualize what was acceptable oscillation, deviation, etc. until actually seeing it from the air. T**he ability to adjust gains and filters during ground tests and while airborne greatly streamlined efficiency.**

HEADING ESTIMATION**—**The ability to fly close formation without knowledge of the lead aircraft's heading was demonstrated during this project (unintentionally, as a by-product of attitude system failure). **As a future unmanned vehicle control law design consideration, a backup mode with simple parameter estimation should be included in the flight control logic to handle lead attitude sensor degradation.**

DATALINK DROPOUTS**—**The impact of datalink dropouts was underestimated by the control designer. When the position vector is in relative terms, the aircraft cannot move far in one time epoch (or two, or three, as was sometimes the case). However, though the small moves do not have an impact on stability, the derivative control is extremely sensitive to instantaneous moves in the error vector. This caused a pulse in the control commands at every data dropout until logic was implemented in the controller that could sense and smooth the data. **In future control systems, logic should be developed to handle periodic data dropouts.**

TIME COMPRESSION **–** Time compression significantly impacted the results of this test. Due to schedule constraints, the first flight of the system was planned for the day after the system was installed, a plan which failed. The system was further planned to be flown every day, including daily fixes to software (which ended up being extremely significant—completely new heading systems, totally new filters and redesigned filter structures…). This was added to a busy daily schedule (double turning every day for the first week). The end result was a negative impact on system performance. The Calspan engineers were available after each sortie, but were gone for the day before the test crew returned from their second sorties. Had more time been available to work with the system between sorties, the DGPS problem would have been identified sooner, and the gains could have been tuned for peak performance (or at least put back to the design levels). The result would most likely have been a complete success rather than a partial success. **Schedule sufficient time between system installation, ground tests, and flights to make modifications and to repair system deficiencies.**

DON'T EXPECT COTS TO WORK AS ADVERTISED—The IMU was a commercial system, and the firmware error that rendered heading and pitch unusable was not foreseen. **Flight test all system components to ensure proper operation prior to the entire system test.**

ON SITE SYSTEM EXPERTISE —During testing, several occasions arose which either would have or did completely stop testing. The DGPS had multiple problems with IP address shifting and 1553 bus difficulty. Units were wrong on one parameter, and requested by the designer to be refined on another mid-test. The DGPS had several new software drops, and the control system received a new software drop daily. The DGPS experienced one hardware failure that required it to be sent back to Ohio. The VSS had multiple problems that required workarounds during testing. Having experts for each system available on site (with the exception of the hardware failure) was the only way that the testing could have been successful. **Have system experts on site for investigation of untested systems, especially with new integration between multiple systems.**

POWER CARTS**—**Power cart availability was a continuing problem. The multiple hardware failures and software integration difficulty caused extensive ground test time that was not scheduled. A lack of power carts delayed testing numerous times, and in one circumstance led to a hardware failure (we used a battery cart which died, damaging a power supply in the VSS). Lack of available ground power carts was identified as a trend item from previous tests at the Test Pilot School. **Schedule required ground equipment for much longer durations than anticipated by test requirements.**

HAVE BACKUP SUPPLIES**—**In a number of cases, backup equipment enabled testing to continue. The test crew had a backup power supply for the VSS, but did not have a new throttle servo, a new DGPS, or a new IMU. Each of these delayed testing at some point. **Have backup hardware equipment available.**

PHOTOGRAPHY—A photographer was not budgeted for. However, due to success of the program, pictures and video were requested. In hindsight, the test team should have planned for a photographer and a chase sortie before the test, which could have been cancelled if not required at the end of the program. **Schedule and budget for documentation of successful tests.**

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